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AIRBORNE PENETRATION
OF RADIOACTIVE CLOUDS

THESIS

AFIT/GNE/PH/83M-7

Terry R. Kling
Capt USAF

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AIRBORNE PENETRATION
OF RADIOACTIVE CLOUDS

THESIS

Presented to the Faculty of the School of Engineering
of the Air Force Institute of Technology

Air University
in Partial Fulfillment of the
Requirements for the Degree of
Master of Science

by

Terry R. Kling
Capt USAF

Graduate Nuclear Engineering

March 1983

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Preface

This independent study began as an effort to perform a follow-up analysis of another thesis on airborne penetration of radioactive clouds. The original thesis was done by B.E. Hickman (Ref 10) and performed a worst case analysis by computing the doses aircrew members would receive when flying through a descending fallout cloud generated by a nuclear surface burst. Military planners are still interested in this problem, due to the proposed dense packing of the MX missiles. An attack on these silos, housing the MX missiles, by megaton or greater sized weapons would present a serious problem for strategic aircraft carrying out their wartime missions. Since these aircraft would be airborne for extended periods of time, penetration of radioactive clouds would be probable.

Presented within are my efforts on extending and improving the previously developed computer code. This code calculates the ionizing dose rate caused by the portion of the radioactive cloud ingested by an aircraft as a function of time. It also computes the dose rate caused by radiation external to the aircraft. The external radiation will be hereafter referred to as sky-shine radiation. Radiation doses from a multiple burst scenario are also computed by an extension of this code.

I am especially thankful to Dr. Charles J. Bridgman for his patience and direction during this research. I am also very grateful for the patience and love my wife, Karen, showed during the period of this research work.

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Abstract:

This report evaluates the threat to aircrew members when their aircraft approaches and subsequently penetrates a descending radioactive cloud generated by a nuclear weapon surface burst.

The computer code developed, during this study, is a revision of the code developed by Hickman. The re-development of Hickman's program consists of a remodeling of the computational methods for sky-shine dose and cloud model. The code also computes the ionizing dose rate an air crew member receives when flying through the radioactive cloud as a function of time. The cloud model developed is patterned after the AFIT (Fallout Smearing) code. A comparison is made between the activities and doses received between 500 and 12,000 meters altitude at increments of 500 meters.

The code computes the doses by considering the cloud size, the aircraft's transit time, the ingestion rate of radioactive particles, the aircraft's distance to the burst, and the aircraft's altitude. A simple extension of the computer code computes the dose received from multiple bursts. The results show that at 9500 meters (^{about} ~~approximately~~ 31,000 ^{about} feet), the total dose to each aircrew member is ^{about} ~~approximately~~ 5 rem after flying through the cloud 1 hour after cloud stabilization. The multiple burst dose is approximately 204 rem under the same conditions as the single burst case. Both the single and multiple burst case use a mission completion time of 8 hours after entering the cloud.

AIRBORNE PENETRATION OF RADIOACTIVE CLOUDS

I. Introduction

Background

The proposed basing of the MX missile system, whether by dense packing or a similar scheme, would definitely be a prime target for an enemy first-strike attack. The numerous radioactive dust clouds generated by such a strike, aided by the prevailing winds, would cause large areas of the continental United States to be exposed to radioactive fallout. Airborne aircraft would also be exposed to these clouds when either entering or approaching them. Strategic aircraft, performing their wartime mission, would be especially susceptible to exposure. The Strategic Air Command has expressed concern about the amount of fallout that Airborne Command Post personnel would be exposed to when flying through these radioactive clouds (Ref 10). The specific dose rates generated by this study provide information to help redirect an aircraft's flight path if location, time of burst, approximate yield and wind profiles are known. By knowing these parameters, the aircraft's altitude could be decreased in order to reduce the dose caused by gamma-ray radiation to the aircrew.

Aircraft penetration of radioactive clouds is hazardous in at least four ways. First, the aircrew is exposed to

ionizing radiation through the aircraft's ventilation system and through the aircraft's skin. Secondly, the aircrew may ingest the radioactive particles. Thirdly, electronic equipment could malfunction if the ionizing dose rate is high enough (Ref 9). Fourth, if the dust particles are large and numerous enough the aircraft's engines could be physically damaged by mass ingestion of the dust particles. This study focuses only on the first hazard. Note that the second hazard could be all but eliminated by having the aircrew put on their oxygen masks.

Problem

No data on previous flights through radioactive clouds could be found. Therefore, comparisons are not made against actual data. Comparisons are made against the data generated by Hickman's (Ref 10) computer code and were found to be approximately 20 percent lower than his for a single megaton size burst. The parameters used in this study were for an EC-135 aircraft. This is the aircraft used as an airborne command post. These parameters are the same for a KC-135 (refueling) aircraft. Parameters for a B-52G could also be used in the computer program (Ref 17). Although, because of time limitations, the author did not compute the dose to a B-52G aircrew member.

The computer program, developed during this study, computes particle size distribution as a function of yield, altitude and fall time for a specific time. With the particle

size distribution known, from sea level on up, the amount of activity at any altitude can be computed. Cabin dose, caused by the ingestion of particles at the aircraft's altitude, and sky-shine dose can then be computed. Total aircrew dose, due to gamma radiation, will then be known.

Scope

This study models the radioactive cloud similarly to Hickman's approach. This computer model computes both the activity that enters the aircraft and the radiation directed through the external skin at specific times and altitudes. There are four major changes compared to Hickman's model. First, the sky-shine dose computational method is changed as to not incorporate Hickman's approximation, but rather a different approximation. Hickman computed sky-shine dose by assuming that the aircraft was positioned at the center of the radioactive cloud for the time it took the aircraft to fly through the cloud. This study computes the sky-shine dose by integrating the normalized horizontal distribution function, $f(x,t)$, from minus to plus infinity. Second, particle size distribution centers are not all set to the cloud's center altitude at stabilization time. The distribution centers are instead set to individual particle altitudes at stabilization time. Third, a shielding approximation was used in computing the sky-shine dose. Fourth, integration from minus to plus infinity of the $f(x,t)$ function was also used to compute the activity caused by the radioactive

particles that enter the cabin. Hickman, on the other hand, used two times the standard deviation of the $f(x,t)$ function as the lateral limits of the radioactive cloud. His program then computed the amount of radioactivity that entered the aircraft during the time it took the aircraft to traverse the radioactive cloud. Also, for internal activity, the numerical integration, used to compute the dose rate at the center of the cabin, used a different value for cabin radius and consequently a different value for this integral was calculated and used in the computer code. These changes are discussed in greater detail later in the text. The results for cabin activity still constitute a worse-case approach. This is because all of the particles that are ingested into the cabin are assumed to remain in the cabin for the duration of the mission. The accumulation of radioactive particles in the cabin is due to cabin pressurization, air conditioning and electronics cooling. Only the mass flow rate from cabin pressurization and air conditioning is used in this study. A different compressor with a different mass flow rate is used for electronics cooling (Ref 19). The aircrew are also exposed to radiation by direct contact and inhalation, although only tissue dose from the external gamma radiation is addressed in this report.

Assumptions

There are several explicit assumptions made in this report. They are:

1. The sky-shine dose is integrated between the times of plus infinity and minus infinity

2. The initial conditions for the stabilized cloud as treated by Bridgman and Bigelow (Ref 1) and remodeled by Hopkins (Ref 2) are applicable

3. The particle size distribution at cloud stabilization time as treated by Bridgman and Hickman (Ref 2) is applicable

4. There is no self shielding of gamma radiation inside the cabin

5. There is no adherence of radioactive particles to the exterior of the aircraft

6. Megaton size thermo-nuclear weapons will be used against the hardened missile silos.

These assumptions are also discussed in more detail later in the text.

Approach

The mathematical development of the computer model and a summary of the results for a single and multiple burst scenario in terms of activity density in Curies per cubic meter versus altitude at various times are presented in Chapter II. The mathematical development for the external dose, caused by both cabin activity and sky-shine, is presented in Chapter III. The results for a single, 1-megaton ground burst are then presented in tabular form. These

tables include the doses received and the particle contributing the most activity at the specified altitude. The mathematical development for incorporation of multiple burst doses into the computer code is presented in Chapter IV. The results are then presented in tabular form for a specific multiple burst scenario. Conclusions and recommendations are presented in Chapter V.

II. Cloud Model

Background

There are two models used almost exclusively to predict radioactive fallout caused by a nuclear burst. These two models are WSEG-10 and DELFIC (Ref 20). WSEG-10 uses empirical functions rather than numerical analyses and computes fallout dose rates in seconds or less on modern computers. WSEG-10 is normally used in operational type studies. DELFIC is used for research work and as a comparison standard because of its excellent predictive capabilities. Unfortunately, DELFIC is cumbersome to use and slow to compute. On the other hand, WSEG-10 fails to account for fractionation, to allow for activity particle size variations in the fallout distribution and to use realistic settling rates.

Patrick (Ref 16) and Patrick et al (Ref 17) investigated aircraft penetration of radioactive clouds using a simplified model. This model was perhaps too simple, since it treated radiation variations, fractionation and particle size distribution rather arbitrarily.

This study, like Hickman's, uses the fallout prediction model developed by Bridgman and Bigelow (Ref 10). This is the AFIT model and produces results which compare favorably with DELFIC (Ref 1). Since this model accounts for fractionation, activity size variations, uses realistic settling rates and computes in seconds or less it is used in the development of the model in this study. Since only the

airborne cloud is used in this study, the $g(t)$ function, which is the normalized rate of arrival of activity on the ground, was not applicable.

Theory

The DELFIC model is considered to be the standard predictive model. The cloud model presented by Bridgman and Bigelow, as modified by Hopkins (Ref 2), is used in this study. Activity size distributions are used which do account for fractionation. These distributions are divided into 100 discrete size groups. The size groups used in this study are from the DELFIC default parameter (Ref 1).

The cloud produced by a nuclear burst consists of hot gases and vapors which rise immediately from the detonation point. The cloud is cooled by radiation and convection until its contents reach the local ambient atmospheric temperature at which point the rise ceases. The cloud stabilizes in 4 to 10 minutes at a height and radius determined by the weapon's yield (Ref 9). Suspended solid particles are formed during the cooling phase and before cloud stabilization. These particles are approximately spherical in shape with sizes ranging from less than a micron to several millimeters for surface bursts.

The radioactive cloud is modeled as an upright volume which approaches a right circular cylinder. This assumes no variation in wind translation from the top to the bottom of the cloud. The radioactivity contained within the cloud is

assumed to be normally distributed in the horizontal direction and individual size groups are assumed normally distributed in the vertical direction. Although, these assumptions are almost never true, they don't really matter for two reasons. First, the sky-shine dose is determined by the particle size activity groups that are near the aircraft. Distant groups are unimportant due to the exponential attenuation of air. Second, for the cabin activity, the aircraft flies through the whole cloud at a constant altitude sweeping out all of the particles that are at that altitude at that time. Figure 1 illustrates this model.

The radioactivity per unit volume of outside air is a function of particle radius, r , and time, t . The activity density is

$$A'''(x, y, z, t) = \int_0^{\infty} A_r'''(x, y, z, r, t) dr \text{ [Ci/m}^3\text{]} \quad (1)$$

Variation of the specific radiation density term, A_r''' , in any of the three spatial directions is assumed to be independent of the other two. It is also assumed that variation in the two horizontal directions is independent of particle size. Therefore, Eq (1) becomes

$$A_r'''(x, y, z, t) = f(x, t)f(y, t) \int_0^{\infty} A_r'(z, r, t) dr \text{ [Ci/m}^3\text{]} \quad (2)$$

where

$$f(x, t) = \frac{1}{\sqrt{2\pi} \sigma_x} e^{-\frac{1}{2} \left(\frac{x - x_0(t)}{\sigma_x(t)} \right)^2} \left[\frac{1}{m} \right] \quad (3)$$

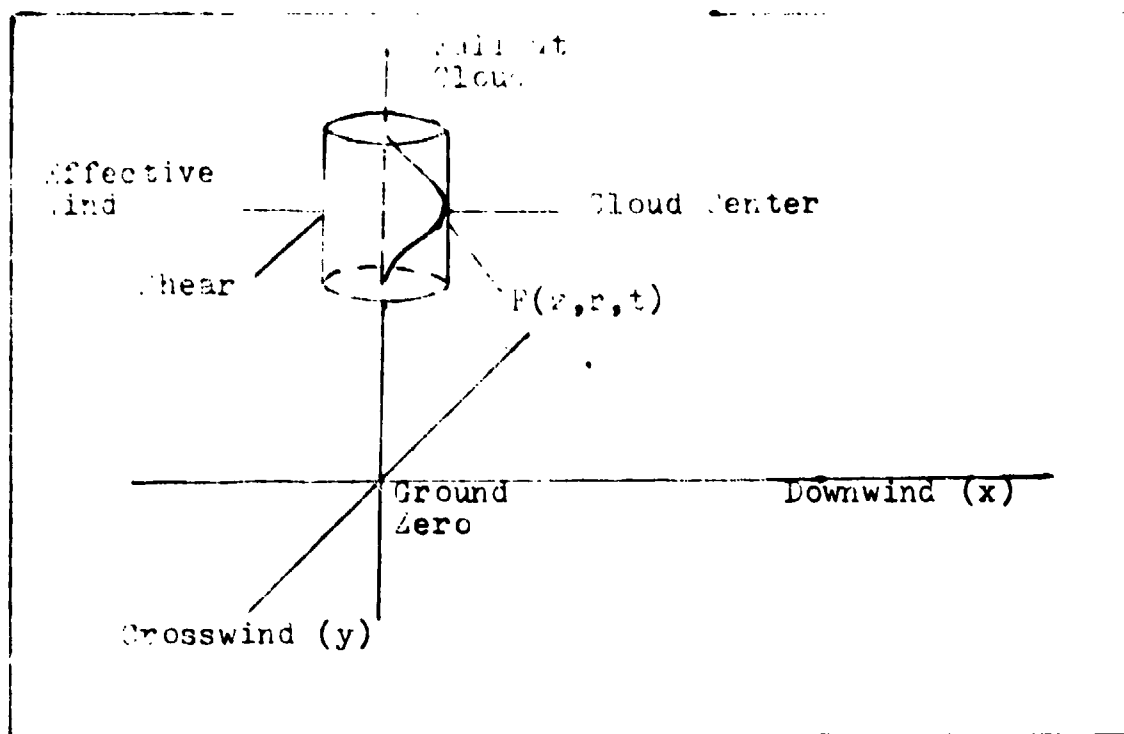


Figure 1. Fallout Cloud Model

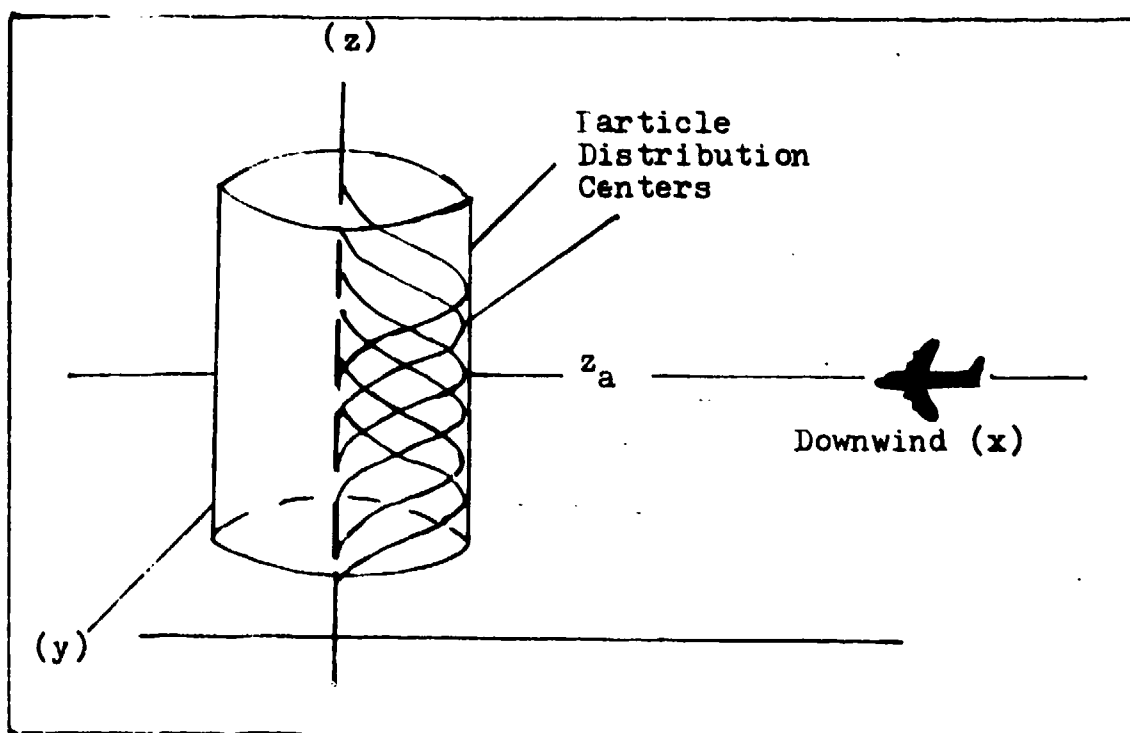


Figure 2. Fallout Cloud at Stabilization Time

and

$$f(y, t) = \frac{1}{\sqrt{2\pi} \sigma_y} e^{-\frac{1}{2} \left(\frac{y - y_0(t)}{\sigma_y(t)} \right)^2} \left[\frac{1}{m} \right] \quad (4)$$

Where σ_x and σ_y are defined later in this section. By replacing the integral in Eq (2) with a summation over the 100 discrete particle size groups, where each group is assumed to consist of a mono-sized particle, r_i , which contains one percent of the total activity one obtains

$$\int_0^\infty A_r'(z, r, t) dr [Ci/m] = \sum_{i=1}^{100} A_i(r, t) f^i(z, t) \quad (5)$$

where

$$f^i(z, t) = \frac{1}{\sqrt{2\pi} \sigma_z} e^{-\frac{1}{2} \left(\frac{z_i - z}{\sigma_z^i} \right)^2} \left[\frac{1}{m} \right] \quad (6)$$

In equations (3) through (6) x is the downwind distance, y is the crosswind distance, z_i is the vertical height for each particle size group, z is the aircraft altitude, hereafter z_a , and the sigmas are the time varying standard deviations. Time of arrival, t_a , was used in the program instead of true time, t . This is an approximation since the time does vary as the aircraft traverses the cloud. But since this time is from one to two minutes, t_a approximately equals t during aircraft passage of the cloud. In WSEG-10, v_x is a constant wind which rotates uniformly with altitude. In this report the aircraft velocity, VAC , is used instead of v_x . Therefore, since the aircraft and the cloud are in the same

medium, VAC is the true airspeed, not groundspeed, of the aircraft.

Eq (4) can now be constructed as

$$A'''(x,y,z,t) = f(x,t)f(y,t) \sum_{i=1}^{100} A_i(r,t)f^i(z,t) \quad (7)$$

The activity $A_i(r,t)$ is equal to one percent of the total cloud activity. This was accomplished by evaluating the cumulative activity size distributions after running the computer code DELFIC with its default particle size distribution (Ref 2). Other activity size distributions could be constructed by the method described by Bridgman and Bigelow (Ref 1). The mean radii of the 100 particle size groups are given in Table I. The time variation of the activity follows the Way-Wigner approximation, $A(t) = A_1 \times t^{-1.2}$, where $A(t)$ is the cloud's activity at time t and A_1 is the activity at unit time. 530 gamma megacuries per kiloton of fission yield was used for the activity at unit time (Ref 9).

Computation of both the sky-shine and cabin ingestion doses ~~is~~^{are} performed by integrating the normalized horizontal distribution function, $f(x,t)$, from minus to plus infinity. This insures that all of the particle size groups, located at the aircraft's altitude, contribute to the dose received. Therefore, this study does not use a worst case approach, as Hickman's did. The methods used to compute sky-shine and cabin ingestion doses are detailed in their respective sections. The assumptions, which allow the above methods to be used,

TABLE I

Mean Radii, in Microns, of the
100 Equal Activity Groups

.48	.92	1.29	1.64	1.99	2.35
2.70	3.07	3.45	3.83	4.23	4.64
5.06	5.49	5.94	6.39	6.87	7.36
7.87	8.39	8.93	9.50	10.1	10.7
11.3	11.9	12.6	13.3	14.0	14.7
15.4	16.2	17.0	17.9	18.7	19.5
20.5	21.5	22.5	23.5	24.6	25.7
26.8	28.0	29.3	30.5	31.9	33.2
34.7	36.2	37.7	39.3	41.0	42.8
44.6	46.5	48.4	50.5	52.7	55.0
57.3	59.8	62.5	65.3	68.2	71.3
74.5	77.7	81.4	85.2	89.2	93.5
98.0	103.	108.	113.	119.	126.
132.	140.	148.	156.	166.	176.
188.	201.	215.	231.	249.	270.
294.	323.	357.	398.	450.	519.
615.	762.	1033.	1873.		

are also defined in these sections. Methods for computing sigma x and y have been developed for both the WSEG-10 (Ref 18) and AFIT (Ref 1) models. Although, since the g(t) function was not used sigma x was never calculated in these two reports. It is assumed that sigma x will behave as sigma y, except without the torroidal growth term. This term is not needed for sigma x since a constant wind in the x direction is assumed. The equations for sigma x and y are

$$\sigma_y^2(t_a) = \sigma_0^2 \left[1 + \frac{8t_a}{T_C} \right] + [\sigma_z \cdot S \cdot t_a] \quad (8)$$

$$\sigma_x^2(t_a) = \sigma_0^2 \left[1 + \frac{8t_a}{T_C} \right] \quad (9)$$

where

$$\sigma_0^2 = \exp[0.7 + \ln(YLD)/3 - 3.25/(4 + [\ln(YLD) + 5.4])] \quad (10)$$

and

$$T_C = \left[\frac{12HC}{60} - \left(\frac{2.5HC}{60} \right) \right] \cdot \left[1 - 0.5 e^{-\frac{(HC)^2}{625}} \right] \quad (11)$$

where

$$HC = 44.0 + 6.1 \cdot \ln(YLD) - 0.205 \cdot [2n(YLD) + 2.42] \cdot |\ln(YLD) + 2.42| \quad (12)$$

The time constant used in WSEG-10, T_C , and t_a are in hours and the standard deviations are in meters. HC is the center height of the cloud and is also from WSEG-10. HC is

in kilofeet and YLD is in megatons. S is the wind shear and is

$$S = \frac{dv_y}{dz} \left[\frac{1}{hr} \right] \quad (13)$$

Shear is assumed to have a constant value of 1 in this study. Sigma z will be defined later in the text. The time, t_a , will always be less than or equal to 3 hours, since this is when the torroidal growth term is assumed to die out (Ref 18).

$F(z, t)$ is evaluated by initially assuming a vertical distribution of the cloud at stabilization time for each activity size group and then following the distribution as it fell to the ground (Ref 2). The stabilized time vertical distributions are assumed to be normal functions with the lower distribution centers at the lower altitudes for the larger particles.

The stabilized altitude for the distribution centers for each activity size group, z_0^i , is calculated from the following formula from Hopkins (Ref 2)

$$z_0^i = C_1 - C_2 D_i \quad (14)$$

where

$$\begin{aligned} \ln C_1 = & 7.889 + 0.34 \cdot \ln Y + 0.001226 \cdot (\ln Y)^2 \\ & - 0.005227 \cdot (\ln Y)^3 + 0.000417 \cdot (\ln Y)^4 \end{aligned} \quad (15)$$

and

$$\begin{aligned} \ln C_2 = & 1.574 - 0.01197 \cdot \ln Y + 0.03636 \cdot (\ln Y)^2 \\ & - 0.0041 \cdot (\ln Y)^3 + 0.0001965 \cdot (\ln Y)^4 \end{aligned} \quad (16)$$

The initial positions of some selected groups are shown conceptually in Figure 2. D_1 is the particle's diameter in microns and Y is the yield in kilotons.

Hopkins developed Eq (14) by executing the DELFIC cloud rise model using the default particle size parameter for several yields and then calculating the altitude of each particle size group at stabilization time. He then empirically fit the vertical mean for each size. Figure 3 illustrates this method.

The vertical distribution for each group at stabilization time was assumed to be distributed normally with a standard deviation of

$$\sigma_z = 0.13 Z_0^1 \quad (17)$$

This is the method, used by WSEG-10, to compute vertical standard deviation; except all particles start at the same initial altitude in WSEG-10. Even though DELFIC does not predict normal distributions for each group the results from this assumption are very close to DELFIC's (Ref 2).

From the initial position of each activity size group, each of the 100 particle size distributions were allowed to fall toward the ground until the aircraft intercepted the cloud. Fall velocities were computed by the method of McDonald (Ref 15), using Davies' (Ref 5) polynomials with a U.S. standard atmosphere divided into a group of layers of constant density and viscosity. The distance a particle

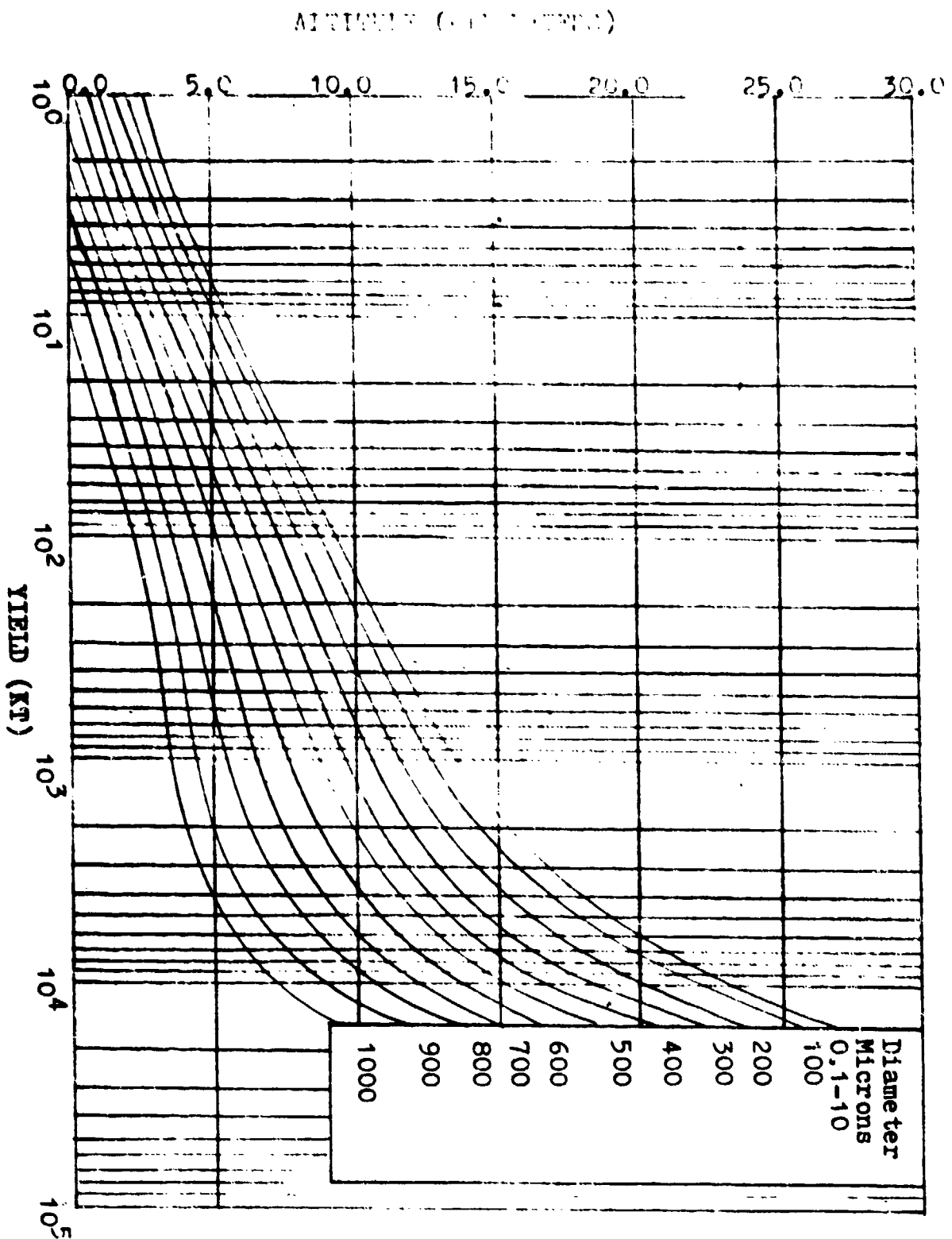


Figure 3. Altitude vs Yield as a Function of Particle Radius

falls in six minutes was selected as the layer thickness. This time was selected by running the fall dynamics section of this study's computer code and computing fall velocities for particles from 1/2 to 1800 microns in radius at altitudes ranging from 1000 to 10,000 meters. Particles of less than 100 microns in radius fell, in six minutes, from slightly over 100 meters to much less than 100 meters, depending on the altitude. For example, a 62.5 micron radius particle at 8000 meters altitude fell at the rate of 1.02 meters per second and a 1000 micron radius particle, at the same altitude, fell at the rate of 16.9 meters per second.

McDonald showed that the Reynold's number squared times the drag coefficient, C_d , of spheres falling through a viscous medium is a function of particle radius, r_i , air density, ρ_{air} , and dynamic viscosity, η . This equates to

$$R^2 C_d = 32 \cdot \rho_{air} \cdot \rho_{part} \cdot g \cdot \frac{r_i}{3\eta} \quad (18)$$

where ρ_{part} is the particle density taken as $2600 \frac{kg}{m^3}$ and g is the gravitational constant. Davies showed that the Reynolds number could be found by the following equations

$$R = R^2 C_d / 24 - 2.3363 \times 10^{-4} \cdot (R^2 C_d)^2 + 2.0154 \times 10^{-6} \cdot (R^2 C_d)^3 - 6.9105 \times 10^{-9} \cdot (R^2 C_d)^4$$

$$\text{for } R^2 C_d < 140$$

and

$$\log(R) = -1.29536 + 0.986 \cdot \log(R^2 C_d) - 0.046677 \\ \cdot [\log(R^2 C_d)]^2 + 0.0011235 \cdot [\log(R^2 C_d)]^3$$

$$\text{for } 3 < R < 10,000 \quad (19)$$

The local velocity is found from

$$v_i = \frac{R\eta}{2\rho_{\text{air}} r_i} \quad (20)$$

Finally, by taking the velocity of the particle times the fall time of each increment the distribution center of each group can be found by

$$z_i(t) = z_s^i - \sum_{j=1}^J v_i^j \Delta t^j \quad (21)$$

where $z_i(t)$ is the distribution center at time t of particle size group i , z_s is the distribution center at cloud stabilization, v_i^j is the velocity of particle size group i during one increment and t is the fall time for that increment.

The activity density for a single burst measured at the aircraft's altitude, z_a , is

$$A'''(x, y, z_a, t) = f(x, t) f(y, t) \sum_{i=1}^{100} \frac{0.1A(t)}{\sqrt{2\pi} \sigma_z^i} \cdot e^{-\frac{1}{2} \left(\frac{z - z_a}{\sigma_z^i} \right)^2} \quad (22)$$

$$\text{where } A(t) = \frac{A^*}{100}$$

$$\text{and } A^* = 530 \times 10^6 \cdot 3.7 \times 10^{10} \cdot \text{YLD} \cdot \text{FF}$$

YLD is the weapon's yield in kilotons and FF is the fission fraction. This activity is the unit time reference activity in disintegrations per second. Therefore, the Way-Wigner decay law must be used to obtain real time activity. Eq (22) is the activity per cubic meter.

Cabin dose, due to ingestion of radioactive particles, and sky-shine dose will be covered in Chapter III. Multiple bursts will be covered in Chapter IV.

III. Cabin Analysis

The parameters used in this study are for an EC-135, an Airborne Command Post aircraft. These parameters would be the same for a KC-135, a refueling aircraft. The EC-135 cruises at 231.5 m/sec and has a skin thickness of 0.063 inches (Ref 17). The EC-135 also has an internal volume of 246.357 cubic meters (Ref 14) and a mass flow rate of outside air into its air conditioning/pressurization system of approximately 150 lbm/min (Ref 13). The aircrew will be exposed to radiation, from both cabin ingested particles and from external radiation at the aircraft's altitude.

Ground-Shine

Ground-shine, cloud radioactivity that has fallen to the ground, was shown by Hickman (Ref 10) to be insignificant. This is true only if the aircraft is flying a few gamma-ray mean free paths (mfp) above the ground. A one MeV gamma-ray has a mfp of approximately 120 meters at sea level (Ref 6). Hickman found the dose rate to an aircraft flying at 305 meters above the ground and through the cloud to be equal to the ground activity times 1×10^{-11} . The author re-calculated Hickman's equations and found the values to be correct. Therefore, ground-shine will be omitted in the final analysis.

Sky-Shine

Approximately 6 minutes after a nuclear ground burst

the radioactive cloud stabilizes. The emission of gamma radiation, from the fission products in this cloud, is the only radiation source addressed in this study. An airborne aircraft will be exposed to this radiation at cloud stabilization time. As the aircraft flies toward the cloud the radiation will increase to a maximum at the horizontal center of the cloud and will then slowly decrease as the aircraft flies away from the cloud. There are two major assumptions made for this model:

1. The mean free path of the gamma radiation is less than $0.1 \sigma_x$.
2. The aircraft is more than $3 \sigma_x$ away from ground zero at t plus 6 minutes.

These assumptions will be discussed in greater detail later in the text.

The reason for the first assumption can be explained as follows. Consider the normalized horizontal distribution function, $f(x, t)$. This function can be rewritten as

$$f(x, t) = \frac{1}{\sqrt{2\pi} \sigma_x} e^{-\frac{1}{2} \left(\frac{VAC \cdot t_a - VAC \cdot t}{\sigma_x} \right)^2} \left[\frac{1}{m} \right] \quad (23)$$

where VAC is the velocity of the aircraft. This function is now integrated with respect to time from minus to plus infinity. After completing this integration one obtains

$$f(x, t) = \frac{1}{VAC} \left[\frac{1}{m} \right] \quad (24)$$

If the mfp of the one MeV gamma-ray is greater than $0.1 \sigma_x$ the $f(x,t)$ function could not be modeled as a true normal distribution function. It follows that as the gamma mfp increases the $f(x,t)$ curve would vary and would then be increasingly divergent from a true normal distribution. This model would then be inaccurate and Eq (24) could not be used. By only using this model for a gamma mfp of less than $0.1 \sigma_x$ the inaccuracy associated with this model can be greatly reduced. The author calculated only a 1 to 2% variation in activity per meter when the mfp was kept below this limit. It can also be noted that the only altitudes affected, for a one MeV gamma-ray, by the above condition are those greater than 11,000 meters. The computer code outputs an error message when the mfp is more than $0.1 \sigma_x$.

The second assumption allows the $f(x,t)$ function to be integrated in time from plus to minus infinity with very little error. The true integration time would be from approximately $t+6$ minutes to t_a plus mission time remaining. The minimum arrival time used in this study was 30 minutes. This time would be equal to approximately $80 \sigma_x$. The integration times used can be compared to the true integration times to determine the error associated with the integration used. Consider the integral

$$f(x,t') = \int_{-\infty}^{+6} \frac{1}{\sqrt{2\pi} \sigma_x} e^{-\frac{1}{2} \left[\frac{VAC(t_a - t')}{\sigma_x} \right]^2} dt' \left[\frac{1}{m} \right] \quad (25)$$

where $t_a = 1/2$ hour to 8 hours. The maximum value Eq (25) has would be at $t_a = 1/2$ hour and this is almost infinitesimal. The contribution from $t' = t_a + 8$ hours to plus infinity is also proportionally small. Figure 4 shows that when the aircraft is more than a few gamma mfp's from the cloud the exponential attenuation of the radiation, by the air, would significantly reduce the radiation received. Spherical divergence also decreases the radiation received by the aircraft. Only when the aircraft is within a few gamma mfp's is the radiation significant.

The sky-shine dose rate is calculated by the use of spherical integration, namely

$$\dot{D} = A'''(x, y, z, t) \int_0^{2\pi} \int_0^{\pi} \int_0^s \frac{\mu_a}{\rho} \frac{e^{-\mu_t s} \cdot s^2}{4\pi s^2} \sin\phi d\theta d\phi ds \quad (26)$$

where $\frac{\mu_a}{\rho}$ is the tissue absorption coefficient, μ_t is the attenuation coefficient of air and s is the radius of the cloud. Equation (26) assumes that $A'''(x, y, z, t)$ does not vary as the differential volume elements are integrated away from the aircraft's location. After integrating Eq (26) one obtains

$$\dot{D} = 1.6 \times 10^{-11} \cdot A''(y, z, t) \cdot \frac{1}{VAC} \cdot \frac{\mu_a}{\rho \mu_t} (1 - e^{-\mu_t s}) \quad (27)$$

where VAC is the aircraft's velocity and 1.6×10^{-11} is a conversion factor to rad-tissue/hr. By letting s approach infinity the exponential term in Eq (27) approaches 1. Eq

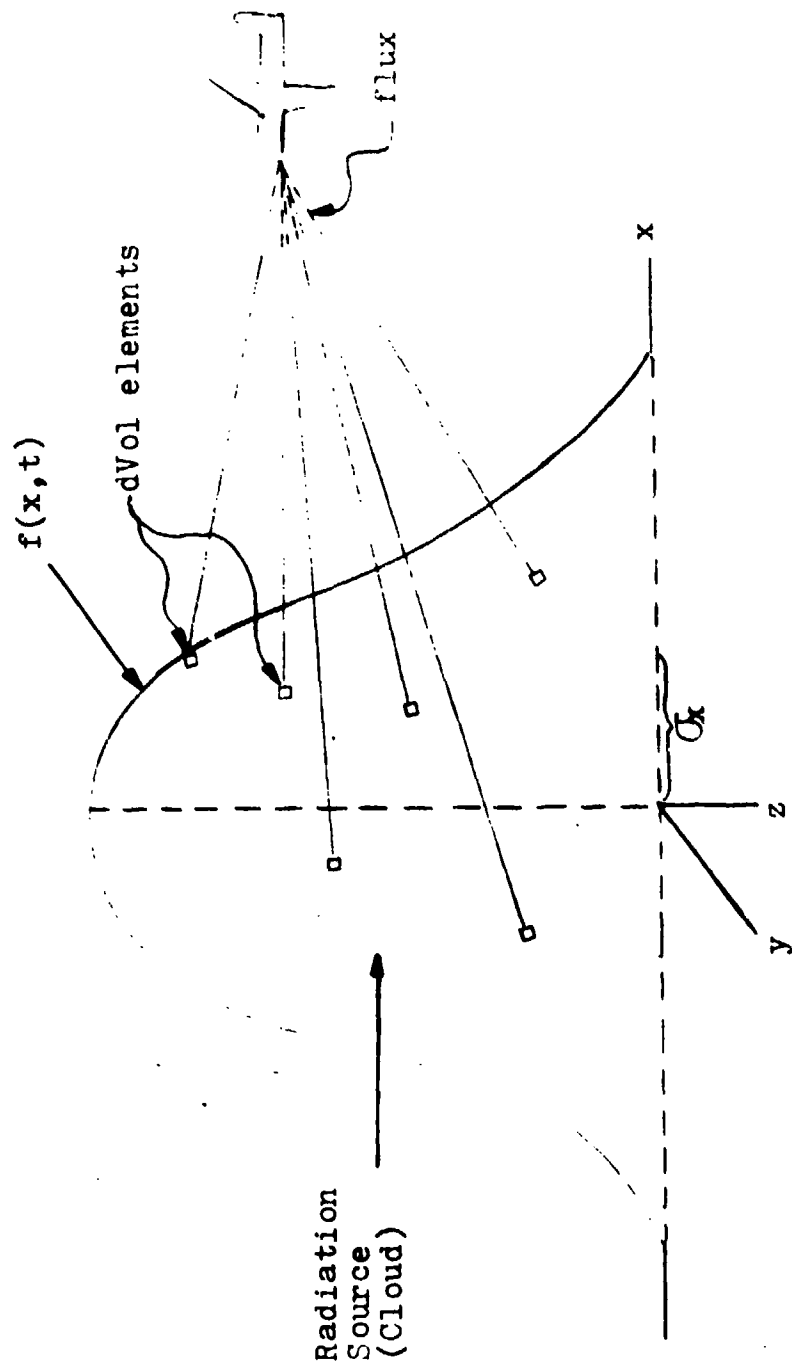


Figure 4. Cloud Model

(27) is the unit time reference dose rate and must be converted to real time by the Way-Wigner decay law.

A shielding model is developed in order to attenuate the sky-shine dose which is transmitted through the aircraft's skin. The cabin area was modeled as a right circular cylinder. The ends of the cylinder were then considered to be infinite shields. This was done to take into account the additional shielding supplied by the equipment and frame surrounding the cabin area. The percent transmitted through the lateral area of the cylinder is then approximately 92 percent. The 1 MeV gamma-rays were further attenuated by the factor $e^{-\mu_t x}$ where μ_t is the attenuation coefficient for aluminum (Ref 12) and x is the skin thickness. This reduced the transmitted gamma-ray energy by an additional 2 percent. Therefore, an attenuation factor of 0.9 was taken times the sky-shine dose. Sky-shine doses are shown in Tables II through X. It can be seen from these Tables that the dose is much more significant at early times and higher altitudes. This is due to the fall of the particles and the decreased attenuation of the gamma radiation at higher altitudes. Also note from Eq (27) that as the aircraft's velocity increases the dose would decrease.

Cabin Ingestion

The aircraft is assumed to fly completely through the cloud in the x direction sweeping out the activity at a constant altitude. There is no variation in the y direction as

the aircraft flies along the y centerline. Therefore, since all of the activity is swept out in the x direction the function $f(x,t)$, which is a normal function, can also be integrated, as was done for the sky-shine dose, from minus to plus infinity. Therefore, $f(x,t) = 1/VAC$ for the cabin ingestion dose computations too. Eq (3) then reduces to

$$A''(y_0, z_a, t_a) = \frac{f(y_0, t_a)}{VAC} \int_0^{\infty} A'_r(z_a, r, t_a) dr \left[\frac{C_1}{m^2} \right] \quad (28)$$

This is illustrated in Figure 5.

The cabin air enters through the fifth stage of the engine air compressor (Ref 19) producing a constant mass flow rate into the cabin of 68.2 kg/min, as noted previously. The mass flow rate is constant at all aircraft velocities and altitudes used in this analysis (Ref 14). The inlet area is

$$\text{Inlet Area} = \frac{\dot{m}}{V_{AC} \cdot \rho_{air}} \quad (29)$$

where ρ_{air} is the air density at the aircraft's altitude. The total activity ingested into the cabin, as the aircraft traverses the cloud, is Eq (28) times Eq (29). The nominal gamma-ray energy is assumed to be 1 MeV (Ref 6). Note from Eq (19) that the activity will decrease as velocity increases.

The flow through the cabin could not be exactly modeled due to the complex behavior of the particles after they enter the cabin. The mean residence time of a particle was computed to be approximately 5 minutes. This would be true only if

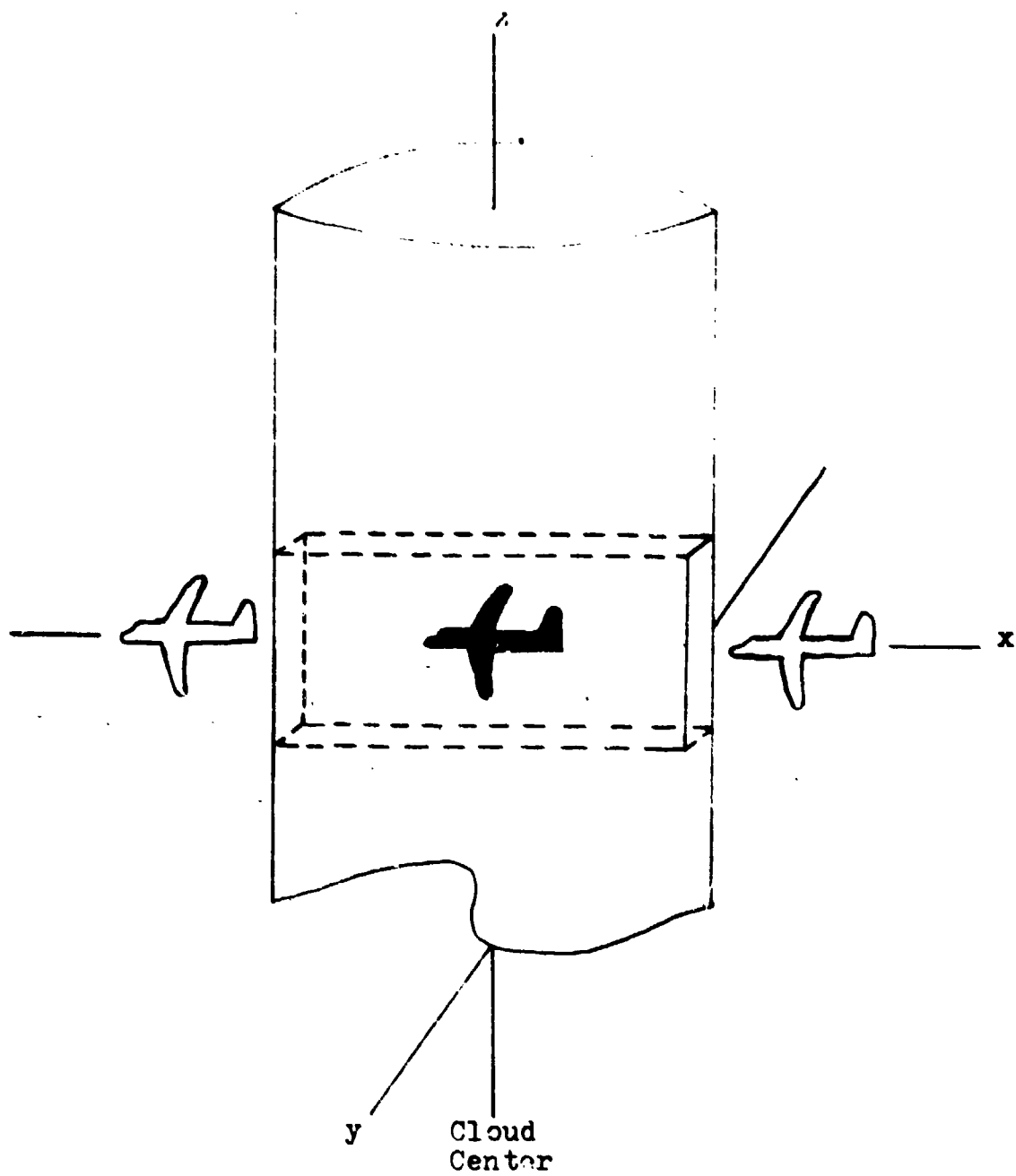


Figure 5. Aircraft Cloud Transit

the particles flowed smoothly through the cabin. This is not true because of the complexity of the cabin's interior. It is assumed that all of the particles are equally distributed in the cabin from aircraft arrival to mission completion time. The cabin activity density would then be the total activity in the cabin divided by the cabin's volume.

The feasibility of filtering the radioactive, dust particles was examined. This was determined to be infeasible due to the size variation of the particles involved (Ref 8). These particles are from 1/2 to 1800 microns in radius. Filtering of these particles would be unlikely, since many filters of various sizes would need to be placed in tandem to filter out even a fraction of the ingested particles. These filters would need to be changed almost continuously when flying through the cloud (Ref 11). Also, damage to the aircraft, caused by the larger particles, may be a greater hazard than the radiation threat. This would be especially true at lower altitudes. This suggests that flying at lower altitudes, in order to reduce crew dose, may not be the best action taken.

To obtain cabin dose rates, the cabin's volume is modeled as a right circular cylinder. It is assumed that self-shielding would be zero and that none of the radioactive particles, which entered the cabin, would be exhausted out of the cabin during the remainder of the aircraft's mission. Neither of these assumptions are true. It would take a very

detailed analysis of the cabin interior to obtain correct shielding and flow rate parameters. The dose rate at the center of the cabin, due to the suspended dust particles, is then

$$\dot{D} = 2 \int_0^{16.027} \int_0^{2.212} \int_0^{2\pi} A \cdot \frac{\mu_a}{\rho} \cdot \frac{e^{-\mu_t(r^2+z^2)^{1/2}}}{4\pi(r^2+z^2)} r d\theta dr dz \quad (30)$$

where r is the radius of the cylinder, z is one-half the height and A is the activity of the ingested particles at one hour. Due to the complexity of Eq (30) a numerical integration, using Simpsons approximation, was performed. The equation, after the numerical integration, is

$$\dot{D} = 3.00 A \frac{\mu_a}{\rho} \quad (31)$$

Figure 6 shows the cabin activity for a 1 Mt burst at altitudes ranging from 500 to 12,000 meters and at arrival times of 1/2 to 8 hours. Note that the activity decreases as the aircraft's altitude decreases and for later arrival times. This suggests that the aircraft's altitude could be decreased to decrease the dose received by an aircrew member. Tables II through X show the cabin dose results from a 1 Mt burst at varying arrival times and altitudes.

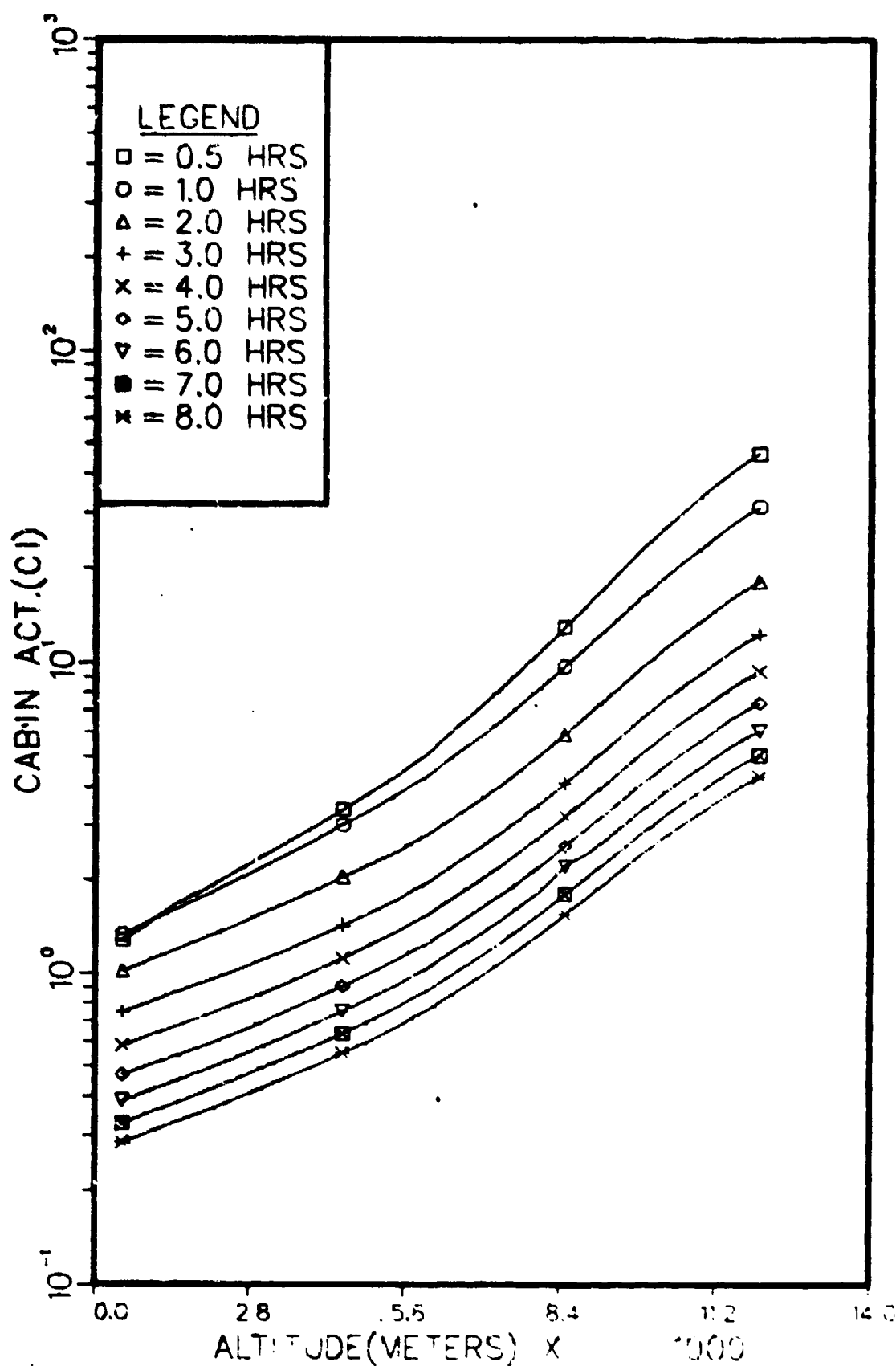


Figure 6. Cabin Activity vs Altitude for a Single Burst

TABLE II

Single Burst Dose Summary for
a 1Mt Burst, TA= 0.5 Hrs, TR= 8.0 Hrs

Altitude (meters)	Cabin Dose (rem)	Sky-Shine Dose (rem)	Total Dose (rem)	Prominent Particle (microns)
12,000	10.455	23.737	34.192	52.7
11,500	9.071	20.595	29.666	62.5
11,000	7.690	17.458	25.148	71.3
10,500	6.474	14.698	21.172	81.4
10,000	5.364	12.178	17.542	93.5
9500	4.394	9.976	14.370	103.0
9000	3.578	8.124	11.702	113.0
8500	2.910	6.607	9.517	126.0
8000	2.378	5.400	7.778	132.0
7500	1.958	4.444	6.402	148.0
7000	1.627	3.694	5.321	156.0
6500	1.368	3.106	4.474	166.0
6000	1.141	2.590	3.731	176.0
5500	0.982	2.230	3.212	188.0
5000	0.857	1.946	2.803	201.0
4500	0.753	1.709	2.462	215.0
4000	0.666	1.517	2.183	231.0
3500	0.591	1.342	1.933	249.0
3000	0.526	1.195	1.721	270.0
2500	0.468	1.062	1.530	270.0
2000	0.416	0.943	1.359	294.0
1500	0.368	0.837	1.205	323.0
1000	0.325	0.737	1.062	323.0
500	0.285	0.648	0.933	357.0

TABLE III

Single Burst Dose Summary for
a 1Mt Burst, TA= 1.0 Hrs, TR= 8.0 Hrs

Altitude (meters)	Cabin Dose (rem)	Sky-Shine Dose (rem)	Total Dose (rem)	Prominent Particle (microns)
12,000	5.062	6.990	12.052	34.7
11,500	4.427	6.113	10.540	41.0
11,000	3.789	5.233	9.022	46.5
10,500	3.226	4.455	7.681	52.7
10,000	2.710	3.742	6.452	57.3
9500	2.257	3.117	5.374	62.5
9000	1.874	2.587	4.461	68.2
8500	1.558	2.152	3.710	74.5
8000	1.303	1.799	3.102	77.7
7500	1.100	1.519	2.619	85.2
7000	0.938	1.295	2.233	89.2
6500	0.808	1.116	1.924	98.0
6000	0.693	0.958	1.651	103.0
5500	0.609	0.842	1.451	108.0
5000	0.540	0.745	1.285	113.0
4500	0.481	0.665	1.146	119.0
4000	0.431	0.595	1.026	126.0
3500	0.387	0.534	0.921	132.0
3000	0.348	0.480	0.828	140.0
2500	0.314	0.434	0.748	148.0
2000	0.284	0.392	0.676	156.0
1500	0.257	0.356	0.613	166.0
1000	0.234	0.323	0.557	166.0
500	0.213	0.294	0.507	176.0

TABLE IV

Single Burst Dose Summary for
a 1Mt Burst, TA= 2.0 Hrs, TR= 8.0 Hrs

Altitude (meters)	Cabin Dose (rem)	Sky-Shine Dose (rem)	Total Dose (rem)	Prominent Particle (microns)
12,000	1.966	1.754	3.720	24.6
11,500	1.731	1.544	3.275	28.0
11,000	1.491	1.330	2.821	31.9
10,500	1.278	1.140	2.418	34.7
10,000	1.082	1.082	2.164	37.7
9500	0.908	0.810	1.718	41.0
9000	0.760	0.678	1.438	44.6
8500	0.637	0.568	1.205	46.5
8000	0.538	0.480	1.018	50.5
7500	0.458	0.409	0.867	52.7
7000	0.395	0.352	0.747	55.0
6500	0.345	0.308	0.653	57.3
6000	0.301	0.268	0.569	62.5
5500	0.268	0.239	0.507	65.3
5000	0.241	0.215	0.456	68.2
4500	0.219	0.195	0.414	71.3
4000	0.199	0.177	0.376	74.5
3500	0.182	0.162	0.344	77.7
3000	0.166	0.148	0.314	81.4
2500	0.152	0.136	0.288	85.2
2000	0.140	0.125	0.265	89.2
1500	0.128	0.115	0.243	93.5
1000	0.118	0.105	0.223	93.5
500	0.109	0.097	0.206	98.0

TABLE V

Single Burst Dose Summary for
a 1Mt Burst, TA= 3.0 Hrs, TR= 8.0 Hrs

Altitude (meters)	Cabin Dose (rem)	Sky-Shine Dose (rem)	Total Dose (rem)	Prominent Particle (microns)
12,000	1.019	0.729	1.748	19.5
11,500	0.900	0.644	1.544	22.5
11,000	0.779	0.557	1.336	24.6
10,500	0.670	0.480	1.150	28.0
10,000	0.570	0.407	0.977	30.5
9500	0.480	0.343	0.823	31.9
9000	0.404	0.289	0.693	34.7
8500	0.340	0.243	0.583	36.2
8000	0.288	0.206	0.494	39.3
7500	0.246	0.176	0.422	41.0
7000	0.212	0.152	0.364	42.8
6500	0.185	0.132	0.317	44.6
6000	0.161	0.115	0.276	48.4
5500	0.144	0.103	0.247	50.5
5000	0.129	0.093	0.222	52.7
4500	0.117	0.084	0.201	55.0
4000	0.107	0.077	0.184	55.0
3500	0.098	0.072	0.170	57.3
3000	0.090	0.065	0.155	59.8
2500	0.083	0.060	0.143	62.5
2000	0.077	0.055	0.132	65.3
1500	0.072	0.051	0.123	68.2
1000	0.066	0.047	0.113	71.3
500	0.062	0.044	0.106	74.5

TABLE VI

Single Burst Dose Summary for
a 1Mt Burst, TA= 4.0 Hrs, TR= 8.0 Hrs

Altitude (meters)	Cabin Dose (rem)x10 ⁻¹	Sky-Shine Dose (rem)x10 ⁻²	Total Dose (rem)	Prominent Particle (microns)
12,000	6.332	39.407	1.027	17.0
11,500	5.609	34.904	0.910	19.5
11,000	4.863	30.262	0.789	21.5
10,500	4.200	26.136	0.681	23.5
10,000	3.580	22.279	0.581	25.7
9500	3.027	18.836	0.491	28.0
9000	2.551	15.876	0.414	29.3
8500	2.153	13.398	0.349	30.5
8000	1.828	11.376	0.297	33.2
7500	1.565	9.743	0.254	34.7
7000	1.354	8.428	0.220	36.2
6500	1.183	7.363	0.192	37.7
6000	1.034	6.437	0.168	39.3
5500	0.921	5.729	0.149	41.0
5000	0.827	5.147	0.134	42.8
4500	0.749	4.663	0.121	44.6
4000	0.682	4.245	0.111	46.5
3500	0.623	3.880	0.101	48.4
3000	0.573	3.565	0.096	50.5
2500	0.528	3.287	0.086	52.7
2000	0.489	3.041	0.079	52.7
1500	0.454	2.823	0.074	55.0
1000	0.423	2.630	0.069	57.3
500	0.394	2.450	0.064	59.8

TABLE VII

Single Burst Dose Summary for
a 1Mt Burst, TA= 5.0 Hrs, TR= 8.0 Hrs

Altitude (meters)	Cabin Dose (rem) $\times 10^{-1}$	Sky-Shine Dose (rem) $\times 10^{-2}$	Total Dose (rem)	Prominent Particle (microns)
12,000	42.252	23.854	0.661	15.4
11,500	37.509	21.176	0.587	17.0
11,000	32.603	18.407	0.511	19.5
10,500	28.221	15.933	0.441	21.5
10,000	24.110	13.611	0.377	22.5
9500	20.419	11.528	0.319	24.6
9000	17.245	9.736	0.270	25.7
8500	14.586	8.235	0.228	28.0
8000	12.406	7.004	0.194	29.3
7500	10.635	6.004	0.166	30.5
7000	9.215	5.203	0.144	31.9
6500	8.067	4.555	0.126	33.2
6000	7.059	3.985	0.111	34.7
5500	6.292	3.552	0.098	36.2
5000	5.667	3.200	0.089	37.7
4500	5.125	2.894	0.080	39.3
4000	4.668	2.635	0.073	41.0
3500	4.262	2.406	0.067	42.8
3000	3.908	2.206	0.061	44.6
2500	3.595	2.030	0.056	44.6
2000	3.314	1.871	0.052	46.5
1500	3.071	1.734	0.048	48.4
1000	2.855	1.612	0.045	50.5
500	2.656	1.499	0.042	50.5

TABLE VIII

Single Burst Dose Summary for
a 1Mt Burst, TA= 6.0 Hrs, TR= 8.0 Hrs

Altitude (meters)	Cabin Dose (rem)x10 ⁻¹	Sky-Shine Dose (rem)x10 ⁻²	Total Dose (rem)	Prominent Particle (microns)
12,000	29.773	15.631	0.454	14.0
11,500	26.483	13.904	0.404	15.4
11,000	23.066	12.110	0.352	17.9
10,500	20.000	10.500	0.305	19.5
10,000	17.119	8.988	0.261	20.5
9500	14.531	7.629	0.222	22.5
9000	12.290	6.453	0.187	23.5
8500	10.404	5.462	0.159	24.6
8000	8.858	4.650	0.135	26.8
7500	7.604	3.992	0.116	28.0
7000	6.589	3.459	0.101	29.3
6500	5.774	3.031	0.088	30.5
6000	5.061	2.657	0.077	31.9
5500	4.514	2.370	0.069	33.2
5000	4.065	2.134	0.062	34.7
4500	3.683	1.934	0.056	34.7
4000	3.357	1.763	0.051	36.2
3500	3.067	1.610	0.047	37.7
3000	2.810	1.475	0.043	39.3
2500	2.586	1.358	0.039	41.0
2000	2.381	1.250	0.036	42.8
1500	2.203	1.157	0.034	42.8
1000	2.043	1.073	0.031	44.6
500	1.898	0.997	0.029	46.5

TABLE IX

Single Burst Dose Summary for
a 1Mt Burst, TA= 7.0 Hrs, TR= 8.0 Hrs

Altitude (meters)	Cabin Dose (rem) $\times 10^{-1}$	Sky-Shine Dose (rem) $\times 10^{-2}$	Total Dose (rem)	Prominent Particle (microns)
12,000	21.872	10.852	0.327	12.6
11,500	19.491	9.671	0.292	14.7
11,000	17.003	8.436	0.254	16.2
10,500	14.776	7.331	0.221	17.9
10,000	12.670	6.286	0.190	19.5
9500	10.772	5.343	0.161	20.5
9000	9.120	4.525	0.137	21.5
8500	7.732	3.837	0.116	23.5
8000	6.588	3.269	0.099	24.6
7500	5.655	2.806	0.084	25.7
7000	4.905	2.434	0.072	26.8
6500	4.298	2.133	0.064	28.0
6000	3.766	1.869	0.056	29.3
5500	3.362	1.668	0.050	30.5
5000	3.028	1.503	0.045	31.9
4500	2.749	1.364	0.041	31.9
4000	2.505	1.243	0.037	33.2
3500	2.291	1.137	0.034	34.7
3000	2.103	1.043	0.031	36.2
2500	1.935	0.960	0.029	37.7
2000	1.784	0.885	0.027	37.7
1500	1.648	0.818	0.025	39.3
1000	1.528	0.758	0.023	41.0
500	1.419	0.704	0.021	41.0

TABLE X

Single Burst Dose Summary for
a 1Mt Burst, TA= 8.0 Hrs, TR= 8.0 Hrs

Altitude (meters)	Cabin Dose (rem) $\times 10^{-1}$	Sky-Shine Dose (rem) $\times 10^{-2}$	Total Dose (rem)	Prominent Particle (microns)
12,000	16.608	7.875	0.245	11.9
11,500	14.825	7.029	0.218	13.3
11,000	12.954	6.142	0.191	15.4
10,500	11.277	5.347	0.166	16.2
10,000	9.687	4.593	0.143	17.9
9500	8.249	3.911	0.122	18.7
9000	6.993	3.316	0.103	20.5
8500	5.936	2.814	0.087	21.5
8000	5.061	2.400	0.075	22.5
7500	4.346	2.060	0.064	23.5
7000	3.770	1.787	0.055	24.6
6500	3.303	1.566	0.049	25.7
6000	2.895	1.373	0.043	26.8
5500	2.583	1.225	0.038	28.0
5000	2.326	1.103	0.034	29.3
4500	2.111	1.001	0.031	30.5
4000	1.924	0.912	0.028	30.5
3500	1.761	0.835	0.026	31.9
3000	1.620	0.768	0.024	33.2
2500	1.490	0.707	0.022	34.7
2000	1.377	0.653	0.020	34.7
1500	1.272	0.603	0.019	36.2
1000	1.180	0.559	0.017	37.7
500	1.094	0.519	0.016	37.7

IV. Multiple Bursts

The computer code was initially developed to handle only a single burst. It was then extended to compute doses caused by multiple bursts. The methods of Hickman (Ref 10) and Crandley (Ref 4) were used to develop this extension.

A field of 150 km by 150 km with 300 bursts spaced proportionally on the field is used in this study. These values can easily be changed. The individual clouds are assumed to overlap each other. This is true when $\sigma_x > L/n_x$ and $\sigma_y > W/n_y$. Where $n_x \cdot n_y = N$, the number of bursts, L =field length and W =field width. Figure 7 illustrates this concept. A calculation is made at arrival time to insure that $\sigma_x > L/n_x$ and $\sigma_y > W/n_y$. The activity density of the cloud is

$$A'''(x, y, z, t_a) = 530 \times 3.7 \times 10^{16} \cdot YLD \cdot FF \cdot f(x, t_a) \cdot f(y, t_a) \cdot f(z, t_a) \left[\frac{\text{dps}}{\text{m}^3} \right] \quad (32)$$

Crandley calculated $f(y, t)$ as

$$f(y, t_a) = \frac{\sqrt{300}}{150} \int_{-75}^{+75} \frac{1}{\sqrt{2\pi} \sigma_y(t_a)} e^{-\frac{1}{2} \left(\frac{y-y'}{\sigma_y(t_a)} \right)^2} dy' \quad (33)$$

which is the sum of the overlapped Gaussian distributions.

The $f(x, t)$ function is found by the same method.

Bridgman and Hickman integrated Eq (33), along with its x direction counterpart, and obtained the activity density at the cloud center at time of arrival as

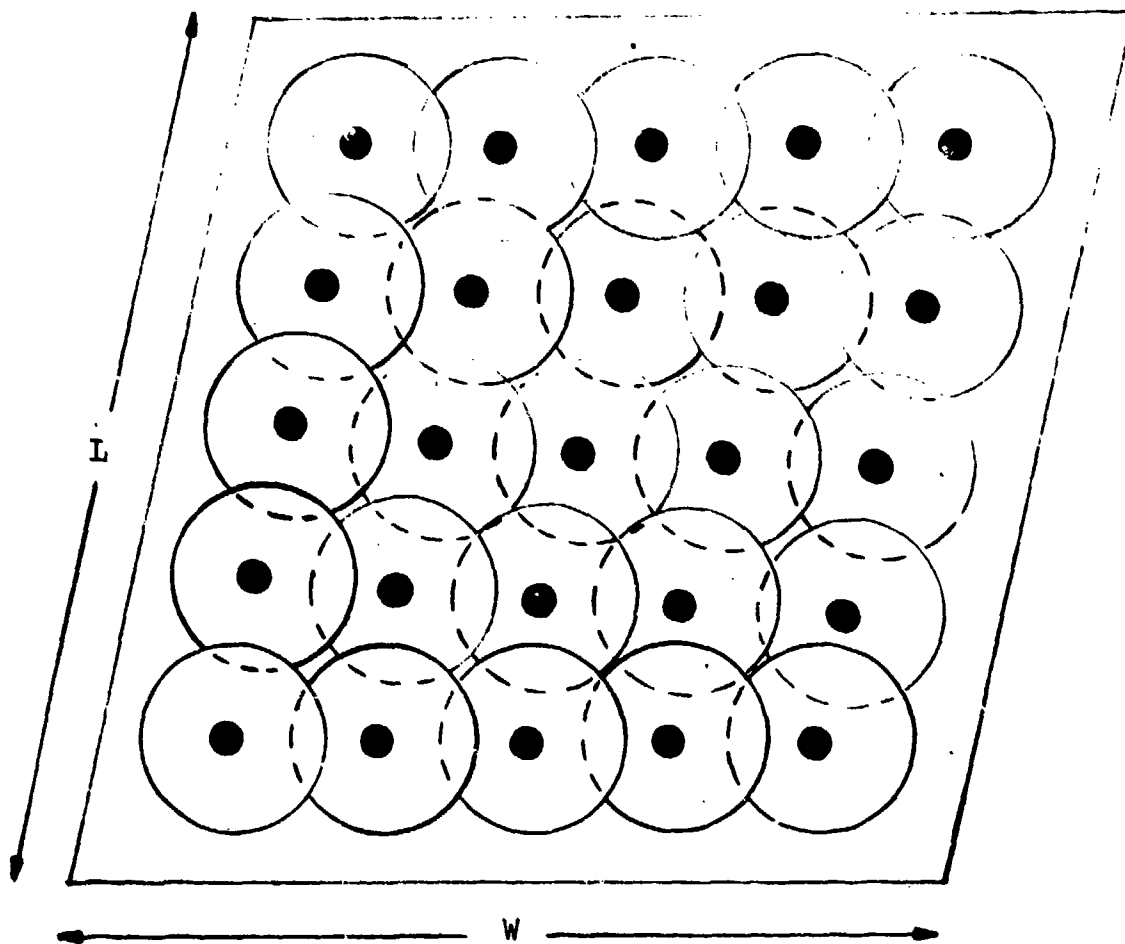


Figure 7. Multiple Burst Cloud Concept

$$A'''(x_0, y_0, z_a, t_a) = \frac{N}{WL} A'_z(z_a, t_a) \left[\frac{C_1}{m^3} \right] \quad (34)$$

They also found the activity per area to be

$$A''(y_0, z_a, t_a) = \frac{N}{L} A'_z(z_a, t_a) \left[\frac{C_1}{m^2} \right] \quad (35)$$

This provides a burst amplification factor for cabin dose of $N/L \cdot 2\pi\sigma_y(t_a)$. This result is used to compute the multiburst cabin dose in this study.

An amplification factor for sky-shine dose is found in a similar manner. The activity density for a single burst is equated to the activity density, Eq(33), for a multiple burst. A burst amplification factor of $N/WL \cdot f(x, t_a) \cdot f(y, t_a)$ was then calculated. The sky-shine dose is then computed for a worst case dose by integrating for the time it took the aircraft to fly over 3 times the standard deviation of the cloud. The aircraft would experience the activity density at cloud center during this time.

The results for the multiple burst case are summarized in Tables XI through XIX. Figure 8 is the cabin activity versus altitude, for arrival times of 1/2 to 8 hours, for the multiple burst case.

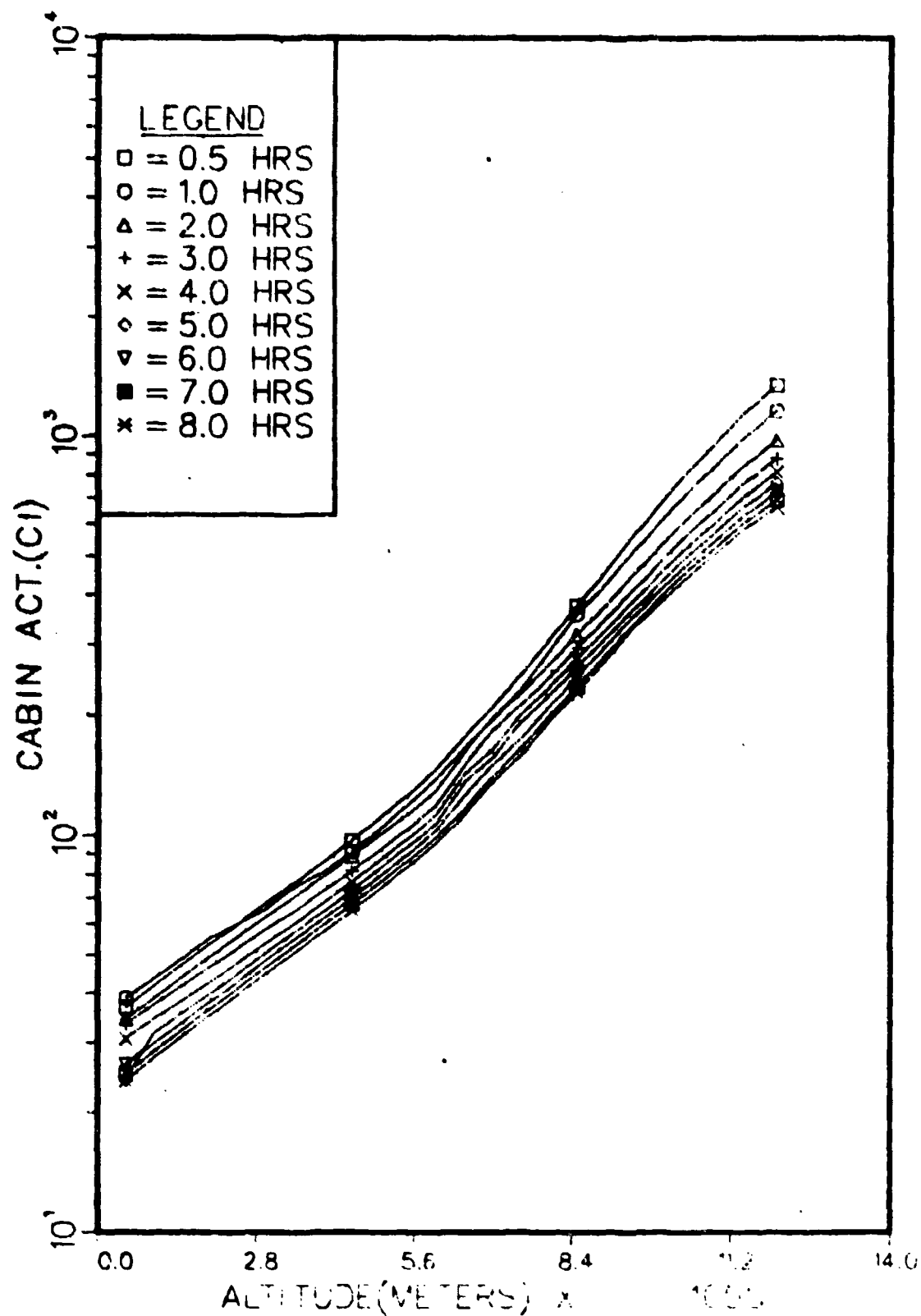


Figure 8. Cloud Activity vs Altitude for a Multiple Burst

TABLE XI

Multiple Burst Dose Summary for
300 One-Mt Bursts, TA= 0.5 Hrs, TR= 8.0 Hrs

Altitude (meters)	Cabin Dose (rem)	Sky-Shine Dose (rem)	Total Dose (rem)	Prominent Particle (microns)
12,000	301.969	677.417	979.446	52.7
11,500	261.995	587.795	849.790	62.5
11,000	222.084	498.254	720.338	71.3
10,500	186.977	419.489	606.466	81.4
10,000	154.922	347.573	502.495	93.5
9500	126.904	284.713	411.617	103.0
9000	103.351	231.872	335.223	113.0
8500	84.054	188.578	272.632	126.0
8000	68.689	154.106	222.800	137.0
7500	56.537	128.843	185.380	148.0
7000	46.997	105.438	152.435	156.0
6500	39.514	88.650	128.164	166.0
6000	32.943	73.910	106.853	176.0
5500	28.374	63.658	92.032	188.0
5000	24.750	55.528	80.278	201.0
4500	21.747	48.790	20.537	215.0
4000	19.233	43.149	62.382	231.0
3500	17.068	38.292	55.360	249.0
3000	15.196	34.094	49.290	270.0
2500	13.513	30.316	43.829	270.0
2000	12.003	26.928	38.931	294.0
1500	10.644	23.879	34.523	323.0
1000	9.382	21.049	30.431	323.0
500	8.243	18.494	26.737	357.0

TABLE XII

Multiple Burst Dose Summary for
300 One-Mt Bursts, TA= 1.0 Hr, TR= 8.0 Hrs

Altitude (meters)	Cabin Dose (rem)	Sky-Shine Dose (rem)	Total Dose (rem)	Prominent Particle (microns)
12,000	186.074	272.788	458.862	34.7
11,500	162.732	238.568	401.300	41.0
11,000	139.292	204.205	343.497	46.5
10,500	118.594	173.861	292.455	52.7
10,000	99.620	146.046	245.666	57.3
9500	82.968	121.633	204.601	62.5
9000	68.875	100.973	169.848	68.2
8500	57.275	83.967	141.242	74.5
8000	47.893	70.212	118.105	77.7
7500	40.426	59.266	99.692	85.2
7000	34.481	50.550	85.031	89.2
6500	29.707	43.551	73.258	98.0
6000	25.493	37.374	62.867	103.0
5500	22.403	32.843	55.246	108.0
5000	19.841	29.088	48.929	113.0
4500	17.696	25.943	43.639	119.0
4000	15.834	23.213	39.047	126.0
3500	14.220	20.846	35.066	132.0
3000	12.788	18.748	31.536	140.0
2500	11.549	16.931	28.480	148.0
2000	10.439	15.304	25.743	156.0
1500	9.465	13.875	23.340	166.0
1000	8.588	12.590	21.178	166.0
500	7.833	11.483	19.316	176.0

TABLE XIII

Multiple Burst Dose Summary for
300 One-Mt Bursts, TA= 2.0 Hrs, TR= 8.0 Hrs

Altitude (meters)	Cabin Dose (rem)	Sky-Shine Dose (rem)	Total Dose (rem)	Prominent Particle (microns)
12,000	105.868	106.006	211.874	24.6
11,500	93.170	93.291	186.461	28.0
11,000	80.252	80.357	160.609	31.9
10,500	68.817	68.907	137.724	34.7
10,000	58.231	58.306	116.537	37.7
9500	48.867	48.932	97.799	41.0
9000	40.892	40.945	81.837	44.6
8500	34.292	34.337	68.629	46.5
8000	28.947	28.987	57.934	50.5
7500	24.663	24.695	49.358	52.7
7000	21.269	21.297	42.566	55.0
6500	18.565	18.589	37.154	57.3
6000	16.189	16.210	32.399	62.5
5500	14.421	14.440	28.861	65.3
5000	12.997	13.014	26.011	68.2
4500	11.778	11.794	23.572	71.3
4000	10.712	10.726	21.438	74.5
3500	9.777	9.790	19.567	77.7
3000	8.949	8.961	17.910	81.4
2500	8.198	8.209	16.407	85.2
2000	7.527	7.536	15.063	89.2
1500	6.919	6.928	13.847	93.5
1000	6.369	6.377	12.746	93.5
500	5.867	5.875	11.742	98.0

TABLE XIV

Multiple Burst Dose Summary for
300 One-Mt Bursts, TA= 3.0 Hrs, TR= 8.0 Hrs

Altitude (meters)	Cabin Dose (rem)	Sky-Shine Dose (rem)	Total Dose (rem)	Prominent Particle (microns)
12,000	73.004	60.474	133.478	19.5
11,500	64.489	53.420	117.909	22.5
11,000	55.771	46.199	101.970	24.6
10,500	48.028	39.784	87.812	28.0
10,000	40.806	33.802	74.608	30.5
9500	34.398	28.494	62.892	31.9
9000	28.906	23.945	52.851	34.7
8500	24.333	20.157	44.490	36.2
8000	20.603	17.067	37.670	39.3
7500	17.599	14.578	32.177	41.0
7000	15.183	12.577	27.760	42.8
6500	13.254	10.979	24.233	44.6
6000	11.561	9.577	21.138	48.4
5500	10.298	8.531	18.829	50.5
5000	9.269	7.678	16.947	52.7
4500	8.415	6.971	15.386	55.0
4000	7.679	6.361	14.040	55.0
3500	7.031	5.824	12.855	57.3
3000	6.474	5.363	11.837	59.8
2500	5.983	4.956	10.939	62.5
2000	5.532	4.583	10.115	65.3
1500	5.128	4.248	9.376	68.2
1000	4.759	3.943	8.702	71.3
500	4.422	3.663	8.085	74.5

TABLE XV

Multiple Burst Dose Summary for
300 One-Mt Bursts, TA= 4.0 Hrs, TR= 8.0 Hrs

Altitude (meters)	Cabin Dose (rem)	Sky-Shine Dose (rem)	Total Dose (rem)	Prominent Particle (microns)
12,000	54.933	39.780	94.713	17.0
11,500	48.656	35.235	83.891	19.5
11,000	42.184	30.548	72.732	21.5
10,500	36.432	26.383	62.815	23.5
10,000	31.056	22.489	53.545	25.7
9500	26.257	19.015	45.272	28.0
9000	22.131	16.027	38.158	29.3
8500	18.677	13.525	32.202	30.5
8000	15.858	11.484	27.342	33.2
7500	13.581	9.835	23.416	34.7
7000	11.749	8.508	20.257	36.2
6500	10.264	7.433	17.697	37.7
6000	8.973	6.498	15.471	39.3
5500	7.986	5.783	13.679	41.0
5000	7.175	5.196	12.371	42.8
4500	6.501	4.708	11.209	44.6
4000	5.917	4.285	10.202	46.5
3500	5.408	3.916	9.324	48.4
3000	4.969	3.598	8.567	50.5
2500	4.582	3.318	7.900	52.7
2000	4.240	3.070	7.310	52.7
1500	3.935	2.850	6.785	55.0
1000	3.666	2.654	6.320	57.3
500	3.415	2.473	5.888	59.8

TABLE XVI

Multiple Burst Dose Summary for
300 One-Mt Bursts, TA= 5.0 Hrs, TR= 8.0 Hrs

Altitude (meters)	Cabin Dose (rem)	Sky-Shine Dose (rem)	Total Dose (rem)	Prominent Particle (microns)
12,000	43.513	28.668	72.181	15.4
11,500	38.627	25.449	64.076	17.0
11,000	33.576	22.121	55.697	19.5
10,500	29.063	19.148	48.211	21.5
10,000	24.829	16.358	41.187	22.5
9500	21.028	13.854	34.882	24.6
9000	17.759	11.700	29.459	25.7
8500	15.021	9.896	24.917	28.0
8000	12.776	8.417	21.193	29.3
7500	10.952	7.216	18.168	30.5
7000	9.490	6.252	15.742	31.9
6500	8.309	5.474	13.783	33.2
6000	7.269	4.789	12.058	34.7
5500	6.480	4.269	10.749	36.2
5000	5.837	3.845	9.682	37.7
4500	5.278	3.478	8.756	39.3
4000	4.807	3.167	7.974	41.0
3500	4.389	2.892	7.281	42.8
3000	4.025	2.652	6.677	44.6
2500	3.703	2.439	6.142	44.6
2000	3.413	2.248	5.661	46.5
1500	3.163	2.084	5.247	48.4
1000	2.940	1.937	4.877	50.5
500	2.735	1.802	4.537	50.5

TABLE XVII

Multiple Burst Dose Summary for
300 One-Mt Bursts, TA= 6.0 Hrs, TR= 8.0 Hrs

Altitude (meters)	Cabin Dose (rem)	Sky-Shine Dose (rem)	Total Dose (rem)	Prominent Particle (microns)
12,000	35.690	21.909	57.599	14.0
11,500	31.746	19.488	51.234	15.4
11,000	27.650	16.973	44.623	17.9
10,500	23.974	14.717	38.691	19.5
10,000	20.521	12.597	33.118	20.5
9500	17.418	10.692	28.110	22.5
9000	14.733	9.044	23.777	23.5
8500	12.471	7.656	20.127	24.6
8000	10.618	6.518	17.136	26.8
7500	9.115	5.595	14.710	28.0
7000	7.899	4.849	12.748	29.3
6500	6.921	4.249	11.170	30.5
6000	6.066	3.724	9.790	31.9
5500	5.411	3.322	8.733	33.2
5000	4.873	2.991	7.864	34.7
4500	4.415	2.710	7.125	34.7
4000	4.025	2.471	6.496	36.2
3500	3.676	2.257	5.993	37.7
3000	3.368	2.067	5.435	39.3
2500	3.100	1.903	5.003	41.0
2000	2.854	1.752	4.606	42.8
1500	2.641	1.621	4.262	42.8
1000	2.449	1.504	3.953	44.6
500	2.276	1.397	3.673	46.5

TABLE XVIII

Multiple Burst Dose Summary for
300 One-Mt Bursts, TA= 7.0 Hrs, TR= 8.0 Hrs

Altitude (meters)	Cabin Dose (rem)	Sky-Shine Dose (rem)	Total Dose (rem)	Prominent Particle (microns)
12,000	30.004	17.431	47.435	12.6
11,500	26.738	15.533	42.271	14.7
11,000	23.325	13.550	36.875	16.2
10,500	20.269	11.775	32.044	17.9
10,000	17.381	10.097	27.478	19.5
9500	14.777	8.854	23.631	20.5
9000	12.510	7.268	19.778	21.5
8500	10.607	6.162	16.229	23.5
8000	9.038	5.250	14.288	24.6
7500	7.757	4.506	12.263	25.7
7000	6.728	3.909	10.637	26.8
6500	5.896	3.425	9.321	28.0
6000	5.167	3.002	8.169	29.3
5500	4.612	2.679	7.291	30.5
5000	4.154	2.413	6.567	31.9
4500	3.771	2.190	5.961	31.9
4000	3.436	1.996	5.432	33.2
3500	3.142	1.825	4.967	34.7
3000	2.884	1.676	4.560	36.2
2500	2.654	1.542	4.196	37.7
2000	2.447	1.422	3.869	37.7
1500	2.261	1.313	3.574	39.3
1000	2.096	1.217	3.313	41.0
500	1.946	1.131	3.077	41.0

TABLE XIX

Multiple Burst Dose Summary for
300 One-Mt Bursts, TA= 8.0 Hrs, TR= 8.0 Hrs

Altitude (meters)	Cabin Dose (rem)	Sky-Shine Dose (rem)	Total Dose (rem)	Prominent Particle (microns)
12,000	25.702	14.284	39.986	11.9
11,500	22.943	12.750	35.693	13.3
11,000	20.048	11.142	31.190	15.4
10,500	17.453	9.699	27.152	16.2
10,000	14.992	8.331	23.323	17.9
9500	12.766	7.095	19.861	18.7
9000	10.823	6.014	16.837	20.5
8500	9.186	5.105	14.291	21.5
8000	7.833	4.353	12.186	22.5
7500	6.725	3.738	10.463	23.5
7000	5.834	3.242	9.076	24.6
6500	5.112	2.841	7.953	25.7
6000	4.481	2.490	6.971	26.8
5500	3.997	2.221	6.218	28.0
5000	3.600	2.001	5.601	29.3
4500	3.267	1.816	5.083	30.5
4000	2.978	1.655	4.633	30.5
3500	2.725	1.514	4.239	31.9
3000	2.507	1.393	3.900	33.2
2500	2.306	1.282	3.588	34.7
2000	2.131	1.184	3.315	34.7
1500	1.968	1.094	3.062	36.2
1000	1.825	1.014	2.839	37.7
500	1.693	0.941	2.634	37.7

V. Conclusions and Recommendations

Conclusions

The results obtained in this study show a decrease in dose received of 20 to 40 percent for sky-shine dose as compared to Hickman's worst case analysis for a single burst. For the sky-shine dose, integrating the $f(x,t)$ function from minus to plus infinity, instead of using Hickman's worst case approximation, reduces the dose received significantly. Also, the 10% shielding approximation contributes to this dose reduction. The cabin ingestion dose results for a single burst approximate Hickman's results. The reason the cabin ingestion doses are close is because Hickman's approximation swept out approximately 96% of the particles; while this study's analysis swept out all of the particles. This still amounts to a significant dose for a multiple burst scenario. The dose received is larger at earlier arrival times and higher altitudes. The dose received by the aircrew is directly dependent on arrival time, aircraft altitude and aircraft velocity. Longer mission times, after cloud penetration, and more bursts, in the multiple burst approach, would proportionally increase the dose each crew member receives.

The feasibility of filtering radioactive particles before they are able to enter the cabin was previously discussed. It was mentioned that the filtering of these particles was infeasible. Verbal information concerning partial filtering

was received by the author (Ref 19). The data supporting this has not been received at the time of this analysis.

A shielding factor was incorporated for the sky-shine dose. This factor, although not exact, is most likely less than the true shielding factor. This is because only the lateral surface area surrounding the crew was shielded by the skin thickness. Shielding of the end areas was assumed to be infinite. This is a trivial assumption since the end areas contain less than 8 percent of the total area.

Attenuation of the radiation by air at varying distances from the cloud was also incorporated into this model. Therefore, this is not a worst case approach to the sky-shine dose. The assumptions made for this model were detailed in the sky-shine section of this report. It was shown for the arrival times and altitudes used that the sky-shine doses received are very accurate.

Recommendations

There are four recommendations to be made. First, a single westerly wind was used in this analysis. A very detailed analysis incorporating nominal wind patterns for various latitudes, longitudes and altitudes for the continental United States could be made. These changes could then be included in a revised computer code. Although, this is a major change and a very difficult one it would give wartime planners a more accurate picture of the radioactive cloud's distribution as a function of its position. Secondly, a

more detailed analysis of the cabin's interior shielding and flow rate parameters could be made to predict a more accurate cabin dose. Due to the complicated nature of the cabin's interior, an interior cabin simulator would probably be needed to accomplish this. Flow rate parameters, size and percent of particles settling out and rate and size of particles exhausted could then be found empirically. Thirdly, a detailed analysis of the materials and their respective thicknesses surrounding the crew would need to be done to obtain a true shielding factor for the sky-shine radiation. Fourth, there is a data source that could be used to bypass the assumption that all the gamma-rays have an energy of 1 MeV (Ref 6). Therefore, depending on the time elapsed after the burst, a more accurate gamma-ray energy could be used. This would cause the parameters which are dependent on gamma-ray energy, such as tissue absorption and attenuation coefficients, to change with time.

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Appendix A

Glossary of FORTRAN Terms

FF = Fission fraction
YLD = Yield in kilotons
ACR = Aircraft range to cloud
VAC = True airspeed
ACA = Aircraft altitude in meters
TR = Mission time remaining
R = Particle radii
TA = Arrival time
VOL = Cabin volume
HR = Arrival time in hours
W = Mass flow rate
HC = Cloud center height
C1 = Intercept for initial particle height equation
C2 = Slope for initial particle height equation
AMAX = Cloud activity
RP = Particle density
PG = Sea level air pressure
TC = Time constant
S0 = Sigma naught
TT = True time used
SX = Sigma x
FX = $f(x, t)$
DALT = Delta altitude

DT = Delta time
 ATOT = Total activity at a specific altitude
 SG = Sigma z at the aircraft altitude
 Z = Particle distribution center height
 T = Temperature
 P = Pressure
 RA = Air density
 DV = Dynamic viscosity
 KV = Kinematic viscosity
 RC = Reynolds number squared times the drag coefficient
 RE = Reynolds number
 VP = Particle velocity
 TI = Time step
 AR = Activity per meter
 PER = Percent of total activity
 PARMAX = Dominent particle's activity
 RADMAX = Dominent particle's radius
 FY = $f(y, t)$
 SY = Sigma y_k
 A2 = Activity per meter squared
 A3 = Activity per meter cubed
 DENS = Air density
 CACT = Cabin activity
 DRATE = Dose rate
 TD = Cabin tissue dose

MUA = Tissue absorption coefficient

MUT = Attenuation coefficient in air

Dl = Dose rate for sky-shine dose

SD = Sky-shine dose

Appendix B

Dose Program

A brief explanation of the dose program and its listing are contained in this appendix. This program can be run either interactively or by card deck. Any initial parameter can be changed, although there are four parameters that are most likely to be changed. These parameters are:

1. Yield in Kilotons (YLD)
2. Aircraft range to burst in meters (ACR)
3. True airspeed in meters per second (VAC)
4. Mission time remaining in hours (TR)

Initially, the program calculates and displays the time of arrival, cloud center height and the aircraft's distance to the burst. It then calculates and displays, for 24 altitudes from 12,000 to 500 meters, activity density, activity area, aircraft altitude, cabin dose, gamma-ray mean free path and sigma x. The last two values are compared with each other to insure an accurate calculation of the sky-shine dose. Dominant particle size and the percent of the total activity it contributes are also displayed.

Another version also calculates and displays the particle distribution center height and the activity per meter at this altitude for each particle.

PROGRAM CADDOS

- C THIS PROGRAM CALCULATES THE CABIN DOSE CAUSED BY CABIN INGESTION
AND SKYSHINE RADIOACTIVITY

REAL RA(100),R(100),AR(100),KV

REAL NUA,MUT,MR,PER(100),MULTI

- C THE DATA FOLLOWING ARE THE RADII OF 100 PARTICLE SIZE GROUPS

DATA(R(1),1=1,35)/.40,.92,1.29,1.64,1.99,2.35,2.70,3.07,3.45,
3.83,4.23,4.64,5.06,5.49,5.94,6.39,6.87,7.34,7.87,8.39,8.93,9.50,
10.1,10.7,11.3,11.9,12.6,13.3,14.,14.7,15.4,16.2,17.,17.9,18.7/
DATA(R(1),1=36,70)/19.5,20.5,21.3,22.5,23.5,24.6,25.7,26.8,28.,
29.3,30.5,31.9,33.2,34.7,36.2,37.7,39.3,41.,42.8,44.6,46.5,48.4,
50.5,52.7,55.,57.3,59.8,62.5,65.3,68.2,71.3,74.5,77.7,81.4,85.2/
DATA(R(1),1=71,100)/89.2,93.5,98.,103.,108.,113.,119.,124.,132.,
140.,148.,156.,164.,174.,180.,201.,215.,231.,249.,270.,294.,323.,
357.,400.,450.,519.,615.,762.,1033.,1073./

- C THE NEXT DATA STATEMENT INPUTS THE FOLLOWING VALUES
- C FF=FISSION FRACTION
- C YLD=WEAPONS YIELD IN KILOTONS
- C ACR=AIRCRAFT RANGE FROM THE BURST
- C VAC=TRUE AIRSPEED
- C ACA=AIRCRAFT ALTITUDE IN METERS
- C TR=TIME REMAINING IN MISSION AFTER AIRCRAFT REACHES CLOUD CENTER

DATA FF,YLD,ACR,VAC,ACA,TR/0.5,1000.,6667200.,231.5,10000.,0./

- C CONVERT RADII TO METERS

DO 40 I=1,100

Following

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PAGES

```

R(I)=R(I)*1.E-06

40 CONTINUE

TA=ACR/VAC

HR=TA/3600.

C VOL=CABIN VOLUME IN CUBIC METERS

VOL=246.356

C W=MASS FLOW RATE IN KGM/MIN OF CABIN AIR INPUT

W=48.2

PRINT*, 'TIME OF ARRIVAL = ', HR, ' HOURS'

PRINT*, 'TRUE AIRSPEED = ', VAC, ' METERS/SECOND'

C HC=CLOUD CENTER HEIGHT IN METERS

HC=(44.+6.10LOG(YLD/1000.))-2958(LOG(YLD/1000.)+2.42)

:RAD5(LOG(YLD/1000.)+2.42)*8304.8

Y=LOG(YLD)

C CURVE FIT VALUES OF INTERCEPT AND SLOPE USED TO FIND DISTRIBUTION

C CENTER HEIGHT OF EACH PARTICLE SIZE GROUP

C1=EXP(7.809+0.340Y+0.001226Y*Y-0.005227Y*Y*Y+0.0004173Y*Y*Y*Y)

C2=EXP(1.574-.001197Y+.003636Y*Y-0.00418Y*Y*Y+.0001965Y*Y*Y*Y)

PRINT*, 'CLOUD CENTER HEIGHT IN METERS = ', HC

PRINT*, 'DISTANCE FROM BURST = ', ACR/1000., ' KM'

C 530 MECACURIES PER KILOTON OF FISSION YIELD ARE PRODUCED

AMAX=530.0E06YLD*FF

C RP=PARTICLE DENSITY

RP=2600.

C PG=SEALEVEL AIR PRESSURE

PG=1.01325E05

```

$$HC1 = HC / 304.8$$

C THE FOLLOWING VALUES ARE USED TO COMPUTE SIGMA X AND Y

$$TC1 = ((12.8(HC1/60.) - (2.58(HC1/60.)^2)882.))$$
$$TC2 = (1.0 - 0.50 \exp(-(NC1002.)/(25.602.)))$$

TC=TC1+TC2+1.05732

$$S0 = \text{EXP}((.7 + \text{LOG}(YLD/1000.)/3.) - 3.25/(4. + (\text{LOG}(YLD/1000.) + 5.4) \times 2.))$$

SO-S081609.344

IF (NR.GT.3.) THEN

II*3.

日英

TT=48

ENDIF
$$SI = ((200(2.)) \div (1. + (0.8TT)/TC)) \div 0.5$$
$$FR = \exp(-.38((B./BX) + 12.1)) / (2.30663082)$$

WLT-SCA/29.

NO 10 K-1,20

22.

DT=344.



ATOT=0.

PRINTS, ' '

PRINTS,'020008V000

PRINTS, ' '

30 20 1-1,100

DIAGNOSTIC

Z=C1-C2*01A

T1=0.0

SZ=0.100Z

100 IF(Z.LE.11000.)THEN

T=200.15-0.00650Z

P=PO*((T/200.15)**0.7509)

ELSE

T=216.65

P=0.2240PO*EXP((-1.502E-04*(Z-11000.))

ENDIF

RA(I)=0.0034040P/T

SM=SQRT(1.40P/RA(I))

C DV-DYNAMIC VISCOSITY AND KV-KINEMATIC VISCOSITY

SV=(1.450E-04*(T**0.5)/(T+110.4))

KV=SV*(1/RA(I))

RC=32.00P+9.006450(R(I)**3.)/13.000(I)*KV**0.2.))

IF(RC.LT.140.)THEN

RE=RC/24.-2.334E-04*(RC**0.2.))+2.0154E-04*(RC**0.3.))-6.91E-07*(RC**0.4.))

ELSE

RE=-1.29536+0.9060LOG10(RC)-0.046677*(LOG10(RC)**2.))+1.1235E-03*

:(LOG10(RC)**3.))

RE=10.00RE

ENDIF

C VP-PARTICLE FALL VELOCITY

VP=(RE*KV/DIA)*(1.+1.165E-07/(R(I)*RA(I)))

Z=Z-VP*DT

TI=TI+DT

IF(TI.LT.TA)THEN

GO TO 100

ENDIF

DALT1=ACA+3.0SZ

IF(Z.GT.DALT1)THEN

GO TO 20

ENDIF

DALT2=ACA-3.0SZ

IF(Z.LT.DALT2)THEN

GO TO 120

ENDIF

C AR=ACTIVITY/METER

AR(I)=0.018ARMAXEXP(-0.30(((Z-ACA)/SZ)002.)))/(2.506634SZ)

IF(90.GT.0.)THEN

GO TO 130

ENDIF

IF(ATOT.EQ.0.)THEN

GO TO 130

ENDIF

IF(AR(I).LT.AR(I-1))THEN

90=02

ENDIF

130 ATOT=ATOT+AR(I)

N=N+1

IF(N.EQ.1)THEN

```

      N=I
    ENDDIF
20 CONTINUE
120 PRINT0, ' '
      I=I-1
      DO 30 J=N,I
        PER(J)=QR(J)*100./ATOT
      30 CONTINUE
C   FIND DOMINANT PARTICLE
      PORMAX=PER(N)
      RADMAX=R(N)
      DO 50 J=N+1,I
        IF (PER(J).GT.PER(J-1)) THEN
          PORMAX=PER(J)
          RADMAX=R(J)
        ENDDIF
      50 CONTINUE
      PRINT0,'DOMINANT PARTICLE SIZE IS ',RADMAX,' N RADIUS'
      PRINT0,'THIS PARTICLE CONTRIBUTES ',PORMAX,'% OF TOTAL ACTIVITY'
      PRINT0,'FOR PARTICLES BETWEEN ',R(N),' AND ',R(I),' N RADIUS'
      SY=((50002.)*(1.+0.8*TT/TC)+(5001.0*HR)*02.)*0.5
      Y0=0.
      FY=EXP(-.50*((Y0/SY)*02.))/(2.506638SY)
C   A2=ACTIVITY/N2 AND A3=ACTIVITY/N3
      A2=ATOT/(2.506638SY)
      A3=A2/(2.506638X)

```

```

PRINT0, ' '
PRINT0, 'ACTIVITY/N2 = ', A2, ' CI/N2'
PRINT0, 'ACTIVITY/N3 = ', A3, ' CI/N3'
PRINT0, 'AIRCRAFT ALTITUDE = ', ACA, ' METERS'
IF (ACA.LE.11000.) THEN
  T=200.-.00659ACA
  P=PG1(T/200.)005.25
ELSE
  P=0.2240PG1EXP(-1.582E-041(ACA-11000.))
  T=216.65
ENDIF
DENS=3.404E-030P/T
CACT=4200/(DENS*VAC160.)
DRATE=CACT03.7E100.00303.4701.6E-0603.6/(VOL0100.)
TD=5.16DRATE0(NR00(-.2)-(NR+TR)00(-.2))
PRINT0, 'CABIN ACTIVITY = ', CACT, ' CI'
PRINT0, 'TISSUE DOSE TO EXPOSURE + ', TR, ' HOURS IS ', TD, ' RADS'
PRINT0, 'DOSE RATE = ', DRATE, ' RADS-TISSUE/HOUR'
C  R0A IS THE TISSUE ABERRATION COEFFICIENT(UA/RND)
C  R0T IS THE ATTENUATION COEFFICIENT FOR SEALEVEL AIR(UT/RND)
R0A=.003
R0T=.006360DENS
IF (1/R0T.GT..100X) THEN
  PRINT0, 'SKYSHINE DOSE INACCURATE DUE TO LARGE GAMMA HFP'
ENDIF
D1=(AT0T03.7E100R0A/R0T)0(FY/VAC)01.6E-11

```

C SO IS THE SKYSHINE DOSE

SD=DIS(NR00(-1.2))10.9

PRINT0,'SKYSHINE DOSE = ',SD,' RADS'

PRINT0,'GAMMA MFP = ',1/MUT,' M', ' SIGMA I = ',SI,' M'

ACA-ACA-BALT

PRINT0,'oo'

:oooooooooooo'

PRINT0,' '

10 CONTINUE

END

Appendix C

Sample Output

TIME OF ARRIVAL = 1. HOURS
TRUE AIRSPEED = 231.5 METERS/SECOND
CLOUD CENTER HEIGHT IN METERS = 13045.2607024
DISTANCE FROM BURST = 833.4 KM

#####

DOMINANT PARTICLE SIZE IS .0000573 M RADIUS
THIS PARTICLE CONTRIBUTES 2.461749223636% OF TOTAL ACTIVITY
FOR PARTICLES BETWEEN 4.0E-7 AND .00014 M RADIUS

ACTIVITY/M2 = 1424.76345945 CI/M2
ACTIVITY/M3 = .1345635162235 CI/M3
AIRCRAFT ALTITUDE = 10000. METERS
CABIN ACTIVITY = 16.92563734593 CI
TISSUE DOSE TO EXPOSURE + 0. HOURS IS 2.710165906343 RADS
DOSE RATE = 1.524252170247 RADS-TISSUE/HOUR
SKYSHINE DOSE = 3.742314327136 RADS
GAMMA HFP = 380.4197171993 M SIGMA X = 4224.012631776 M
#####

#####

DOMINANT PARTICLE SIZE IS .0000625 M RADIUS
THIS PARTICLE CONTRIBUTES 2.7792234145% OF TOTAL ACTIVITY
FOR PARTICLES BETWEEN 4.0E-7 AND .000140 M RADIUS

ACTIVITY/M2 = 1261.061961604 CI/M2
ACTIVITY/M3 = .1191700063179 CI/M3
AIRCRAFT ALTITUDE = 9500. METERS
CABIN ACTIVITY = 14.09640219990 CI
TISSUE DOSE TO EXPOSURE + 0. HOURS IS 2.257143343141 RADS
DOSE RATE = 1.269463070917 RADS-TISSUE/HOUR
SKYSHINE DOSE = 3.116761001795 RADS
GAMMA HFP = 357.7315035207 M SIGMA X = 4224.012631776 M
#####

#####

DOMINANT PARTICLE SIZE IS .0000602 M RADIUS
THIS PARTICLE CONTRIBUTES 3.150430001707% OF TOTAL ACTIVITY
FOR PARTICLES BETWEEN 4.0E-7 AND .000156 M RADIUS

ACTIVITY/M2 = 1112.902601756 CI/M2
ACTIVITY/M3 = .1051169942393 CI/M3
AIRCRAFT ALTITUDE = 9000. METERS

ACTIVITY/M2 = 982.5337868340 C1/M2
ACTIVITY/M3 = .09279659741972 C1/M3
AIRCRAFT ALTITUDE = 8300. METERS
CABIN ACTIVITY = 9.731151713217 C1
TISSUE DOSE TO EXPOSURE + 8. HOURS IS 1.938170947545 RADS
DOSE RATE = .0763440631975 RADS-TISSUE/HOUR
SKYSHINE DOSE = 2.151989700415 RADS
CANDIA MFP = 317.1593399168 H SIGMA I = 4224.612631776 H
#####

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ACTIVITY/M2 = 071.4502070734 C1/M2
ACTIVITY/M3 = .00230510137764 C1/M3
AIRCRAFT ALTITUDE = 0000. METERS
CABIN ACTIVITY = 0.137004121741 C1
TISSUE DOSE TO EXPOSURE + 0. HOURS IS 1.302912933240 RADS
DOSE RATE = .7327043920054 RADS-TISSUE/HOUR
SKYSHINE DOSE = 1.779110490039 RADS
GAMMA HFP = 299.0079074054 H SIGMA I = 4224.012631776 M
#####

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73

#####

ACTIVITY/M2 = .704.218658963 C1/M2
ACTIVITY/M3 = .06451078697433 C1/M3
AIRCRAFT ALTITUDE = 7000. METERS
CNRIN ACTIVITY = 5.850428642863 C1
TISSUE DOSE TO EXPOSURE + 0. HOURS IS .9380617127323 RADS
DOSE RATE = .5275043045302 RADS-TISSUE/HOUR
SKYSHINE DOSE = 1.295316155996 RADS
SIGNAL HPF = 266.3997270896 H SIGNAL X = 4224.042631776 M
#####

XX

ACTIVITY/M2 = .642.021124410 C1/M2
ACTIVITY/M3 = .06063646524513 C1/M3
AIRCRAFT ALTITUDE = 6500. METERS
CABIN ACTIVITY = 3.047191246125 C1
TISSUE DOSE TO EXPOSURE + 0. HOURS IS .000166033354 RADS
DOSE RATE = .4545209547271 RADG-TISSUE/HOUR
SKYSHINE DOSE = 1.119730656754 RADS
DANNA HFP = 251.7452090220 H SIGMA I = 4224.012631776 H
#####

[illegible]

74

ACTIVITY/M2 = 582.6621127496 CI/M2
ACTIVITY/M3 = .05582456448533 CI/M3
AIRCRAFT ALTITUDE = 6000. METERS
CADIN ACTIVITY = 4.331344835113 CI
TISSUE DOSE TO EXPOSURE + 8. HOURS IS .693533630046 RADS
DOSE RATE = .3900429100036 RADS-TISSUE/HOUR
SKYSHINE DOSE = .9576746506434 RADS
GAMMA HFP = 232.07372717274 M SIGMA X = 4224.012631776 M

DOMINANT PARTICLE SIZE IS .000108 U RADIUS
THIS PARTICLE CONTRIBUTES 6.48280041174% OF TOTAL ACTIVITY
FOR PARTICLES BETWEEN .0000235 AND .000215 U RADIUS

ACTIVITY/M2 = 540.9092956743 C1/M2
ACTIVITY/M3 = .951694391411 C1/M3
AIRCRAFT ALTITUDE = 5500. METERS
CABIN ACTIVITY = 3.306309395237 C1
TISSUE DOSE TO EXPOSURE + 0. HOURS TO .609473490523 EARL
DOSE RATE = .3427003370979 RADG-TISSUE/HOUR
SKYLINE DOSE = .0415076243333 RADG
GAMMA RFP = 225.3677073699 H SIGMA Z = 4229.012631776 H
#####

DOMINANT PARTICLE SIZE IS .000113 IN RADIUS
THIS PARTICLE CONTRIBUTES 6.72201540477% OF TOTAL ACTIVITY
FOR PARTICLES BETWEEN .000311 AND .000215 IN RADIUS

ACTIVITY/M2 = 365.9157352909 CI/M2
ACTIVITY/M3 = .04770102027077 CI/M3
AIRCRAFT ALTITUDE = 3000. METERS
CABIN ACTIVITY = 3.371044070062 CI
TISSUE WEIGHT TO EXPOSURE + 0. HOURS IS .5397705049700 RADS
DOSE RATE = .3033023940061 RADS-TISSUE/HOUR
SKYCHINE DOSE = .7453495993333 RADS
GAMMA WFP = 213.3740710370 H SIGMA I = 4224.012631776 M
#####

75

DOMINANT PARTICLE SIZE IS .000119 M RADIUS
THIS PARTICLE CONTRIBUTES 7.351264862247% OF TOTAL ACTIVITY
FOR PARTICLES BETWEEN .0000377 AND .000231 M RADIUS

ACTIVITY/M2 = 476.1265627609 CI/M2
ACTIVITY/M3 = .04496835178329 CI/M3
AIRCRAFT ALTITUDE = 4500. METERS
CABIN ACTIVITY = 3.006621914219 CI
TISSUE DOSE TO EXPOSURE + 0. HOURS IS .4814261512975 RADS
DOSE RATE = .2707630060953 RADS-TISSUE/HOUR
SKYSHINE DOSE = .6447740369179 RADS
GAMMA HFP = 202.2167670766 M SIGMA I = 4224.012631776 M
#####

#####

DOMINANT PARTICLE SIZE IS .000126 M RADIUS
THIS PARTICLE CONTRIBUTES 7.79079703346% OF TOTAL ACTIVITY
FOR PARTICLES BETWEEN .0000428 AND .000231 M RADIUS

ACTIVITY/M2 = 449.2233207004 CI/M2
ACTIVITY/M3 = .04242744239620 CI/M3
AIRCRAFT ALTITUDE = 4000. METERS
CABIN ACTIVITY = 2.690170070727 CI
TISSUE DOSE TO EXPOSURE + 0. HOURS IS .4307352663343 RADS
DOSE RATE = .242269476115 RADS-TISSUE/HOUR
SKYSHINE DOSE = .5940034009961 RADS
GAMMA HFP = 191.7609093245 M SIGMA I = 4224.012631776 M
#####

#####

DOMINANT PARTICLE SIZE IS .000132 M RADIUS
THIS PARTICLE CONTRIBUTES 0.231601697654% OF TOTAL ACTIVITY
FOR PARTICLES BETWEEN .0000404 AND .000249 M RADIUS

ACTIVITY/M2 = 425.1324353735 CI/M2
ACTIVITY/M3 = .04015214945600 CI/M3
AIRCRAFT ALTITUDE = 3500. METERS
CABIN ACTIVITY = 2.415943306329 CI
TISSUE DOSE TO EXPOSURE + 0. HOURS IS .3060935360403 RADS
DOSE RATE = .2173697667313 RADS-TISSUE/HOUR
SKYSHINE DOSE = .5341730632300 RADS
GAMMA HFP = 101.9790354102 M SIGMA I = 4224.012631776 M
#####

DOMINANT PARTICLE SIZE IS .000166 M RADIUS
THIS PARTICLE CONTRIBUTES 10.07067964400Z OF TOTAL ACTIVITY
FOR PARTICLES BETWEEN .0000713 AND .000294 M RADIUS

[illegible]

DOMINANT PARTICLE SIZE IS .000166 M RADIUS
THIS PARTICLE CONTRIBUTES 10.5464193448% OF TOTAL ACTIVITY
FOR PARTICLES BETWEEN .0000777 AND .000214 M RADIUS

XX

DOMINANT PARTICLE SIZE IS .000176 μ RADIUS
THIS PARTICLE CONTRIBUTES 11.04501543100% OF TOTAL ACTIVITY
FOR PARTICLES BETWEEN .0000014 AND .000323 μ RADIUS

ACTIVITY/K2 = 316.972091051 C1/K2
ACTIVITY/K3 = .02990100037749 C1/K3
AIRCRAFT ALTITUDE = 500. METERS
CABIN ACTIVITY = 1.33004729406 C1
TISSUE DOSE TO EXPOSURE + 0. HOURS IS .2130770504356 RADDS
DOSE RATE = .119030346746 RADDS-TISSUE/HOUR
SKYLINE DOSE = .394234733307 RADDS

Appendix D

Microsoft BASIC Version

A Microsoft BASIC version of the computer code was also developed. This program performs the same computations and outputs the same values as the FORTRAN version, but was developed for use on a microcomputer. The program listing is included in this appendix for those who may want to run the code on a microcomputer.

```

10 RENOCADIM DOSE PROGRAM MODEL 20
20 RENIPROGRAM REVISED 17/11/821
30 DIM RA(100),R(100),AR(100)
40 OPEN#6,"P:"OUTPUT:DEF CLOG(X)=.43434LOG(X)
50 INPUT"FF,YLB,ACR,VAC,TR,ACA?";FF,YLB,ACR,VAC,TR,ACA
60 DATA .40,.92,1.29,1.64,1.99,2.35,2.70,3.07,3.45,3.83
70 DATA 4.23,4.64,5.06,5.49,5.94,6.39,6.87,7.36,7.87,8.39
80 DATA 8.93,9.50,10.1,10.7,11.3,11.9,12.6,13.3,14.0,14.7
90 DATA 15.4,16.2,17.0,17.9,18.7,19.5,20.5,21.5,22.5,23.5
100 DATA 24.6,25.7,26.8,28.0,29.3,30.5,31.9,33.2,34.7,36.2
110 DATA 37.7,39.3,41.0,42.8,44.6,46.5,48.4,50.5,52.7,55.0
120 DATA 57.3,59.8,62.5,65.3,68.2,71.3,74.5,77.7,81.4,85.2
130 DATA 89.2,93.5,98.0,103,108,113,119,126,132,140
140 DATA 148,156,166,176,188,201,215,231,249,270
150 DATA 294,323,357,390,450,519,615,762,1033,1873
160 FOR IX=1 TO 100:READ R(IX):R(IX)=R(IX)*1E-06:NEXT
170 TA=ACR/VAC:NR=TA/3600:VOL=246.357:W=68.2
180 PRINT"TIME OF ARRIVAL(Nr)=";NR
190 HC=(44.+6.18LOG(YLB/1000)-0.2054(LOG(YLB/1000)+2.42)+ABS(LOG(YLB/1000)+2.42))*304.0
200 Y=LOG(YLB)
210 C1=EXP(7.809+.348Y+.0012264Y^2-.0052278Y^3+.0004178Y^4)
220 C2=EXP(1.574-.0011978Y+.0036368Y^2-.00418Y^3+.00019658Y^4)
230 PRINT"CLOUD CENTER HEIGHT(Nr)=";HC
240 ANXI=530E+06*YLB*FF
250 BP=2600:PB=1.01325E+05

```

```

260 HC=HC/304.0;TC1=120HC/60-(2.50(HC/60)^2);TC2=(1.-.50EXP(-(HC^2))/(25.^2));TC=TC1+TC2*1.05732
270 SD=EXP((0.7+LOG(YLD/1000)/3)-3.25/(4.+(LOG(YLD/1000)+5.4)^2))*1609.344
280 IF NR>3. THEN TT=3. ELSE TT=NR
290 SX=((SD^2)*(1.+(0.8TT)/TC))^1.5
300 FX=EXP(-.50((0/SX)^2))/(2.50668SX)
310 DALT=ACA/5
320 FOR K=1 TO 7
330 SB=0;BT=360;ATBT=0;I=0
340
PRINT06;PRINT06,TAB(2);"ITERATION";SPC(5);"RADIUS(N)";SPC(5);"ACT. (CI/N)";SPC(4);"ALT. (N)";PRINT06
350 FOR I=1 TO 100
360 B=R(I)*2
370 Z=C1-C2*B
380 TI=0;BT=0.1002
390 IF Z<=11000 THEN 410
400 IF Z>11000 THEN 420
410 T=200.15-0.006502;P=P00(T/200.15)^5.2509;GOTO 430
420 T=216.65;P=.2240P00EXP(-1.502E-040(Z-11000))
430 RA(I)=.0034040P/T;SH=SHR(1.40P/RA(I));BV=(1.450E-040T^1.5)/(T+110.4);KV=BV/RA(I)
440 RC=320P+.006650(R(I)^3)/(30RA(I)*(KV^2));IF RC>140 THEN 460
450 RE=RC/24-2.334E-040(RC^2)+2.0154E-060(RC^3)-6.91E-090(RC^4);GOTO 470
460 RE=-1.29534+.9060CLOG(RC)-.0466770(CLOG(RC)^2)+1.1233E-030(CLOG(RC)^3);RE=10^RE
470 VP=RE/KV/0;BC=1.+1.165E-07/(R(I)*RA(I));VP=VP*BC
480 Z=Z-VP*BT
490 TI=TI+BT
500 IF TI<TA THEN 390

```

```

510 IF Z>ACA+30SZ THEN 610
520 IF Z<ACA-30SZ THEN 620
530 AR(1)=.01800010EIP(-0.50*((Z-ACA)/SZ)^2)/(2.5066305Z)
540 IF SB>0 THEN 570
550 IF ATOT=0 THEN 570
560 IF AR(1)<AR(1-1) THEN SB=SZ
570 PRINT06,I,R(1),AR(1),Z
580 ATOT=ATOT+AR(1)
590 I=I+1
600 IF I=1 THEN L=1
610 NEXT I
620 PRINT06:PRINT06,"Z TOT. ACT. ";SPC(3);"PARTICLE RADIUS(N)":PRINT06
630 I=I-1
640 FOR J=L TO I
650 PER=(AR(J)/ATOT)*100
660 PRINT06,PER,R(J)
670 NEXT J
680 SY=((30^2)*8*(1.+(0.1TT)/TC)+(300100R)^2)^.5;YB=0.
690 FY=EIP(-.50*((YB/SY)^2))/(2.50660SY)
700 A2=ATOT/(2.50660SY)
710 A3=A2/(2.50660SX)
720 PRINT06:PRINT06,"ACTIVITY/M2 =" ;A2;"CI/M2","ACTIVITY/M3 =" ;A3;"CI/M3"
730 PRINT06,"ACFT ALT =" ;ACA;"M","ARRIVAL TIME =" ;HR;"HOURS"
740 PRINT06,"ACFT VELOCITY =" ;VAC;"M/SEC"
750 IF ACA<=11000 THEN T=200-.00450ACA ELSE T=216.65
760 IF ACA<=11000 THEN P=P00(T/200)^5.25 ELSE P=.2240P00EIP(-1.502E-04*(ACA-11000))

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770 DE=3.484E-030P/T
780 CACT=A20N/(DE*VAC060)
790 DRAT=CACT03.7E+100.00303.4701.6E-0603.6/(VOL0100)
800 TD=50DRAT*(HR^-.2-(HR+TR)^-.2)
810 PRINT04,"DISTANCE FROM BURST =" ;ACR/1000;"KM"
820 PRINT04,"CABIN ACTIVITY =" ;CACT;"CI"
830 PRINT04,"DOSE RATE =" ;DRAT;"RADS TISSUE PER HOUR"
840 PRINT04,"TISSUE DOSE TO EXPOSURE =" ;TR;"HOURS IS";TD;"RADS"
850 NMA=.003;NMT=.0063610E
860 IF 1/NMT>.10SX THEN PRINT04,"SKYSHINE DOSE INACCURATE DUE TO LARGE GAMMA MEAN FREE PATH"
870 D1=(AT013.7E+100NMA/NMT)*(FY/VAC)01.6E-11
880 SD=010(HR^-.1.2)
890 PRINT04,"SKYSHINE DOSE =" ;SD;"RADS"
900 PRINT04,"GAMMA MFP =" ;1/NMT;" M", "SIGMA I =" ;SX;" M"
910 ACA=ACA-DALT
920 IF K=5 THEN ACA=500
930 IF K=6 THEN ACA=250
940 NEXT K
950 END

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Vita

Terry R. Kling was born 25 May 1947 in Lancaster, Pennsylvania. He grew up there and completed high school in 1965. He entered Millersville State College in January 1966. He then enlisted in the Air Force in June 1966. After completing technical school in Denver, Colorado he was stationed at Griffiss AFB, N.Y. as a Bombing-Navigation Systems technician. In June 1974 he entered Oklahoma State University and received his B.S.Ch.E. in May 1977. He graduated from Officer's Training School in September 1977. He was then assigned to the Rocket Propulsion Laboratory at Edwards AFB, Ca. as a Test and Design Engineer. Captain Kling was assigned to the Air Force Institute of Technology's master's degree program in Nuclear Effects in August 1981.

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER AFIT/GNE/PH/83-7 ^M	2. GOVT ACCESSION NO. AD-A135848	3. REPORT'S CATALOG NUMBER
4. TITLE (and Subtitle) AIRBORNE PENETRATION OF RADIOACTIVE CLOUDS		5. TYPE OF REPORT & PERIOD COVERED M Thesis
7. AUTHOR(s) Terry R. Kling Capt USAF		6. PERFORMING ORG. REPORT NUMBER
9. PERFORMING ORGANIZATION NAME AND ADDRESS Air Force Institute of Technology (AFIT-GR) Wright-Patterson AFB, OH 45433		8. CONTRACT OR GRANT NUMBER(s)
11. CONTROLLING OFFICE NAME AND ADDRESS		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)		12. REPORT DATE March 1983
		13. NUMBER OF PAGES 91
		15. SECURITY CLASS. (of this report) UNCLASSIFIED
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE
16. DISTRIBUTION STATEMENT (of this Report) Approved for Public Release; Distribution Unlimited		
17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)		
18. SUPPLEMENTARY NOTES Approved for public release; LAW AFR 180-17. LYNN E. WOLAYER Docs for Research and Professional Development Air Force Institute of Technology (ATC) Wright-Patterson AFB OH 45433		
19. KEY WORDS (Continue on reverse side if necessary and identify by block number) Dust Cloud Penetration Crew Survivability/Vulnerability Radioactive Dust Clouds Nuclear Radiation		
20. ABSTRACT (Continue on reverse side if necessary and identify by block number) This report evaluates the threat to aircrew members when their aircraft approaches and subsequently penetrates a radioactive cloud generated by a nuclear weapon surface burst. A computer program is developed to compute the ionizing dose rate an aircrew member receives when flying through a radioactive cloud as a function of time. This is a revision to a previous code developed by Hickman. Comparisons are made between activities and doses (Continued on Reverse)		

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BLOCK 20: ABSTRACT (Continued)

received between 500 and 12,000 meters altitude. The doses are computed by considering the cloud size, the aircraft's transit time, the ingestion rate of radioactive particles, the aircraft's distance to the burst and the aircraft's altitude. An extension to the computer program also computes the dose received from a multiple burst scenario. The results show, for a single burst, the total ionizing dose each aircrew member receives is approximately 5 rem. This is for an altitude of 9500 meters one hour after cloud stabilization. The multiple burst case, under the same conditions, is approximately 204 rem. Both the single and multiple burst cases use a mission completion time of 8 hours after entering the cloud.

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